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V. Svetlosanov and W.G. Knisel, *Editors*

EUROPEAN AND UNITED STATES CASE STUDIES IN APPLICATION OF THE CREAMS MODEL

V. Svetlosanov and W.G. Knisel, Editors

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PREFACE

Land resources are a very important component of the interaction between man and the environment. The current trend is toward an intensification of land use, which is dictated by the intensive growth of the world's population, and by the increasing demand for agricultural products. In many cases, the intensification of land use may lead to negative consequences, among which the erosion process and chemical pollution from agricultural fields will play a very important role.

Between 1978-1980, a group of scientists was brought together at the International Institute for Applied Systems Analysis (IIASA) to work within the Resources and Environment Area; the purpose was to examine the environmental problems in agriculture, as well as to collect and assess the existing models which described the environmental impacts of agriculture.

The research mainly addressed the problems of soil erosion, nitrogen leaching, and phosphorus and pesticide losses. A complex field-level model (CREAMS--the acronym for Chemicals, Runoff, and Erosion from Agricultural Management Systems), developed by the U.S. Department of Agriculture, Agricultural Research Service, was chosen as a mathematical tool for the investigation of these problems. It was made operative on the IIASA computer in 1980 and researchers from eight National Member Organization (NMO) countries used this tool for concrete investigations in the analysis of agricultural policy in their countries. This volume is a compilation of papers and summarizes the results of these applications.

Janusz Kindler
Chairman
Resources & Environment Area

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INTRODUCTION

W.G. Knisel
V. Svetlosanov

The world food problem is now one of the more important issues facing mankind. The global population growth and the increasing demand for agricultural products on the one hand will lead to the extension of agricultural land, and on the other, to the intensification of land use. Both situations have detrimental effects on the environment. The strong intensification of land use without understanding its negative consequences in many cases will lead to the degradation of soil. The loss of top soil through water and wind erosion, loss of organic matter and the changing of the soil structure, salinization and alkalinization--all of these processes need to be taken into consideration when agricultural ecosystems are analyzed. Therefore, the problem of interaction between agricultural management and the environment embraces specialists in many fields of investigations, that is, agriculturists, economists, soil scientists, engineers, systems analysts, and so on.

The processes in agricultural systems being nonlinear and complicated, mathematical models may be one of the important instruments for consequential estimation of agricultural management. There are many models which deal with different environmental consequences of agricultural production (Haith, 1982). Of course, there are no perfect and universal models to account for all environmental consequences of management systems. Most of the models describe only a hydrologic component (water percolation, runoff, evapotranspiration). Some consider the erosion/sediment yield and pesticide components, while some include the salinization process, and others include plant nutrient components from fields.

Among all the models which consider the different phenomena of agricultural systems, only two include a combination for the consideration of all of the processes: hydrology, erosion/sediment yield, pesticides, and plant nutrients from field-size management units (Donigian et al., 1977; Knisel, 1980). Of these two, the ARM model (Donigian et al., 1977) requires observed data to calibrate the model coefficients before it can be used in the simulation mode.

Several countries require investigation of the complex environmental consequences of agricultural management; therefore, the International Institute for Applied Systems Analysis' (IIASA) Resources and Environment Area decided to transfer one of these models to the Institute. The physically based CREAMS model program developed by the US Department of Agriculture (Knisel, 1980) was made operational in 1980 on the IIASA computer and used by many scientists. The users of this model were from the following countries: Czechoslovakia, FRG, Finland, Poland, Sweden, United Kingdom, United States, and the USSR. The organizational work was done by former IIASA scientists, Drs. G. Golubev and I. Shvytov.

As stated before, the main objective of this work was to perform the quantitative evaluation of the consequences of the agricultural management in different countries. The collateral objective was to make validation studies of the CREAMS model where possible.

The planned case studies are completed now, and some of them are included in this publication. Four papers (Holy et al., 1981; Holy et al., 1982; Morgan, 1980; and Svetlosanov, 1982) were published by IIASA earlier, and are not included in this publication but they are alluded to in the general discussion on the use of the CREAMS model in different countries.

Field measurements of runoff, erosion, plant nutrients, and pesticides use are not available in all pollution problem areas. Field data collection and laboratory analyses are time consuming and expensive. Sometimes pollution problems are perceived, but quantitative measurements are not available and it is desirable to use some method (model) to estimate the effects of an agricultural management system. For these reasons, the case studies of CREAMS model application are very different. The studies can be grouped into three categories:

1. Those where some observed data are available for model validation (Finland, England);
2. Those where some observed data are available for model validation with model extension for simulation (CSSR, FRG, USA);
3. Those without observed data and only model simulations are generated to examine possible problems associated with management (Sweden, USSR, Poland).

The editors gratefully acknowledge the continued support of this project by IIASA, specifically, Drs. G. Golubev and J. Kindler. The efforts of the contributing authors are also greatly appreciated.

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CREAMS: A SYSTEM FOR EVALUATING MANAGEMENT PRACTICES ON FIELD-SIZE AREAS*

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CREAMS: A SYSTEM FOR EVALUATING MANAGEMENT PRACTICES ON FIELD-SIZE AREAS

Mathematical models are required to assess nonpoint source pollution and to evaluate the effects of management practices in the United States, so as to adequately respond to the Water Quality Legislation of the past 10 years. Action agencies must assess nonpoint source pollution from agricultural areas, identify problem areas, and develop conservation practices to reduce or minimize sediment and chemical losses from fields where potential problems exist. Monitoring every field or farm to measure pollutant movement is impossible, and landowners have to know the potential benefits before they apply conservation practices. Only through the use of models can pollutant movement be assessed and conservation practices be planned most effectively.

In 1978, the U.S. Department of Agriculture, Agricultural Research Service, began a national project to develop relatively simple, computer-efficient mathematical models for evaluating nonpoint source pollution. A model that does not require calibration was planned since very little data suitable for calibrating a model are available. The initial efforts were concentrated on a field scale, since that is where conservation management systems are applied. A field was defined as an area with a relatively homogeneous soil that was under a single management practice, and was small enough that rainfall variability was minimal. Requirements for the model were that it be simple and yet represent a complex system, be physically based and not require calibration, be a continuous simulation model, and have the potential to estimate runoff, erosion, and transport of chemical in a solution and attached to the sediment. A field scale model, CREAMS, capable of assessing these conditions and meeting these requirements has been developed.

The purpose of this paper is to present the concepts, to briefly describe each component of the model, to describe model applicability, and to describe an application of CREAMS--a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. A complete description of the model and instructions for its use have been published by the U.S. Department of Agriculture, Science and Education Administration as Conservation Research Report No. 26 (14).

MODEL DEVELOPMENT

Simple mathematical expressions have been used for many years as simple models in hydrology, erosion, and sedimentation. The Universal Soil Loss Equation (USLE) (17) is a simple mathematical model that relates average annual soil loss (A) to an average annual rainfall erosivity factor (R), a soil erodibility factor (K), a slope length and steepness factor (LS), a cover-management factor (C), and a supporting practice factor (P) in the form A = RKLSCP.

The USLE is a much used and powerful model for estimating long-term erosion. Values for its factors are readily available, and calculations are quick and easy. Values for the C and P factors can be changed to represent different management and cover conditions, and model calculations repeated to estimate the influence of a change in management.

In the present-day needs for evaluating runoff, percolation, erosion/sediment transport, and associated dissolved and sediment adsorbed chemical losses from farms, one simple relationship is insufficient. Also, long-term averages may be meaningless, as in the case of a toxic pesticide that may only be a problem for a few days after application. Interactions between the various components of the transport system prevent the use of single straightforward calculations. However, the physical processes can be represented by a logical series of mathematical expressions which can be solved repetitively and easily with high-speed computers. First, the modeler identifies the important physical processes that must be represented to provide the accuracy and detail of information needed from the model. Formulation of the model expresses the problem for a few days after application. Interactions between the various components of the transport system prevent the use of single, straightforward calculations. However, the physical processes can be represented by a logical series of mathematical expressions which can be solved repetitively and easily with high-speed computers. First, the modeler identifies the important physical processes that must be represented to provide the accuracy and detail of information needed from the model. Formulation of the model expresses the modeler's concepts of the physical system and his ideas of the order of processes. Computer efficiency is also important, especially when a model is to be used many times to evaluate a system as complex as nonpoint source pollution. If a model is to show effects of management practices, the necessary equations and parameters that reflect the practices must be incorporated in the model.

Models are developed for a specific purpose to accomplish a specific job, and therefore, application of the model outside specific conditions can result in erroneous answers. Use of a model for estimating streamflow from large basins would likely give misleading estimates of runoff from a 5-acre area. For example, average infiltration could be satisfactory for the basin scale, but for the field scale, temporal and spatial variations in infiltration may be important. Sediment yield estimates for large basins often require careful description of channel processes, whereas an accurate description of erosion by raindrop impact on overland flow areas may be most important for estimating sediment yield from fields.

REVIEW OF MODELS

Passage of the Clean Waters Act, PL 92-500, in 1972 resulted in the need for mathematical models to evaluate nonpoint source pollution from diffuse agricultural areas. These needs resulted in a proliferation of model development. Although hydrology and erosion models were available, few models for chemical transport were available. Models for evaluating nonpoint source pollution have been assembled, oftentimes by "piggy-backing" of erosion and chemical components onto hydrology models for both field- and basin-sized areas.

Crawford and Donigian (3) developed the pesticide runoff transport (PRT) model to estimate runoff, erosion, and pesticide losses from field-size areas. The hydrologic component of the PRT model is the Stanford watershed model (4), and the erosion component was developed by Negev (11). The Stanford watershed model was one of the first computer simulation hydrologic models and was developed for basin-sized areas.

Donigian and Crawford (5) incorporated a plant nutrient component with the basic PRT model to develop the agricultural runoff model (ARM). The hydrology, erosion, and pesticides components are the same as the PRT model. The ARM is also for field-sized areas. Both the PRT and ARM models require data for calibration.

Frere et al. (7) developed an agricultural chemical transport model (ACTMO) to estimate runoff, sediment yield, and plant nutrients from field- and basin-sized areas. The hydrology component is the USDA Hydrograph Lab model (9), which is based on an infiltration concept. The erosion component is based on the rill and interrill erosion concepts and USLE modifications developed by Foster et al. (6). The ACTMO model does not require calibration.

Bruce et al. (2) developed an event model (WASCH) to estimate runoff, erosion, and pesticide losses from field-sized areas for single runoff-producing storms. The model requires calibration to the specific site of consideration.

Beasley et al. (1) developed the ANSWERS model to estimate runoff, erosion, and sediment transport from basin-sized areas. The model does not have a chemical component. It has been used to identify sources of erosion and areas of deposition within the basin.

The ARM, WASCH, and ANSWERS models are expensive to operate and cannot be used economically for long-term simulation. Long-term simulation and risk analysis are desirable for examining probable levels exceeded for toxic pesticide concentrations.

Models that require calibration to evaluate parameter values are generally calibrated for a specific site and practice. If relationships for the physical processes are not carefully formulated, parameter values can be seriously distorted. Calibration of a model with data for a specific site and management practice may give erroneous results when the model is applied to a different site or management practice without recalibration. Therefore, minimization of the need for calibration is desirable. A model is most useful when values for its parameters are readily available as functions of easily measured features of the site and practice being evaluated. Both modelers and model users should be aware of problems associated with calibration, availability of parameter values, parameter distortion by inadequate watershed representation, inaccurate results from poorly formulated equations, and excessive use of computer time. We sought to minimize these problems with CREAMS.

CREAMS MODEL STRUCTURE

CREAMS consists of three major components: hydrology, erosion/sedimentation, and chemistry. The hydrology component estimates runoff volume and peak rate, infiltration, evapotranspiration, soil water content, and percolation on a daily basis, or if detailed precipitation data are available, calculates infiltration at histogram breakpoints. The erosion component estimates erosion and sediment yield including particle distribution at the edge of the field on a daily basis. The chemistry component includes elements for plant nutrients and pesticides. Stormloads and average concentrations of sediment associated and dissolved chemicals in the runoff, sediment, and percolate fractions are estimated.

The Hydrology Component

This component consists of two options, depending upon availability of rainfall data. Option 1 estimates storm runoff when only daily rainfall data are available. If hourly or breakpoint (time-intensity) rainfall data are available, Option 2 estimates storm runoff by an infiltration-based method.

Option 1: Williams and LaSeur (16) adapted the Soil Conservation Service (15) curve number method for simulation of daily runoff. The method relates direct runoff to daily rainfall as a function of curve number (Figure 1). Curve number is a function of soil type, cover, management practice, and antecedent rainfall. The relationship of runoff, Q, to rainfall, P, is

$$Q = \frac{(P-0.2S)^2}{P + 0.8S} \tag{1}$$

where S is a retention parameter related to soil moisture and curve number. An equation for water balance is used to estimate soil moisture from:

$$SM_t = SM + P - Q - ET - O \tag{2}$$

where SM is initial soil moisture, SM_t is soil moisture at day t, P is precipitation, Q is runoff, ET is evapotranspiration, and O is percolation below the root zone.

The percolate component uses a storage routing technique to estimate flow through the root zone. The root zone is divided into 7 layers--the first layer is 1/36 of the total root zone depth, the second layer 5/36 of the total, and the remaining layers, all equal in thickness, are 1/6 of the root zone depth. The top layer is approximately equivalent to the chemically active surface layer and the layer where interrill erosion occurs. Percolation from a layer occurs when soil moisture exceeds field capacity. Amount of percolation depends on saturated hydraulic conductivity.

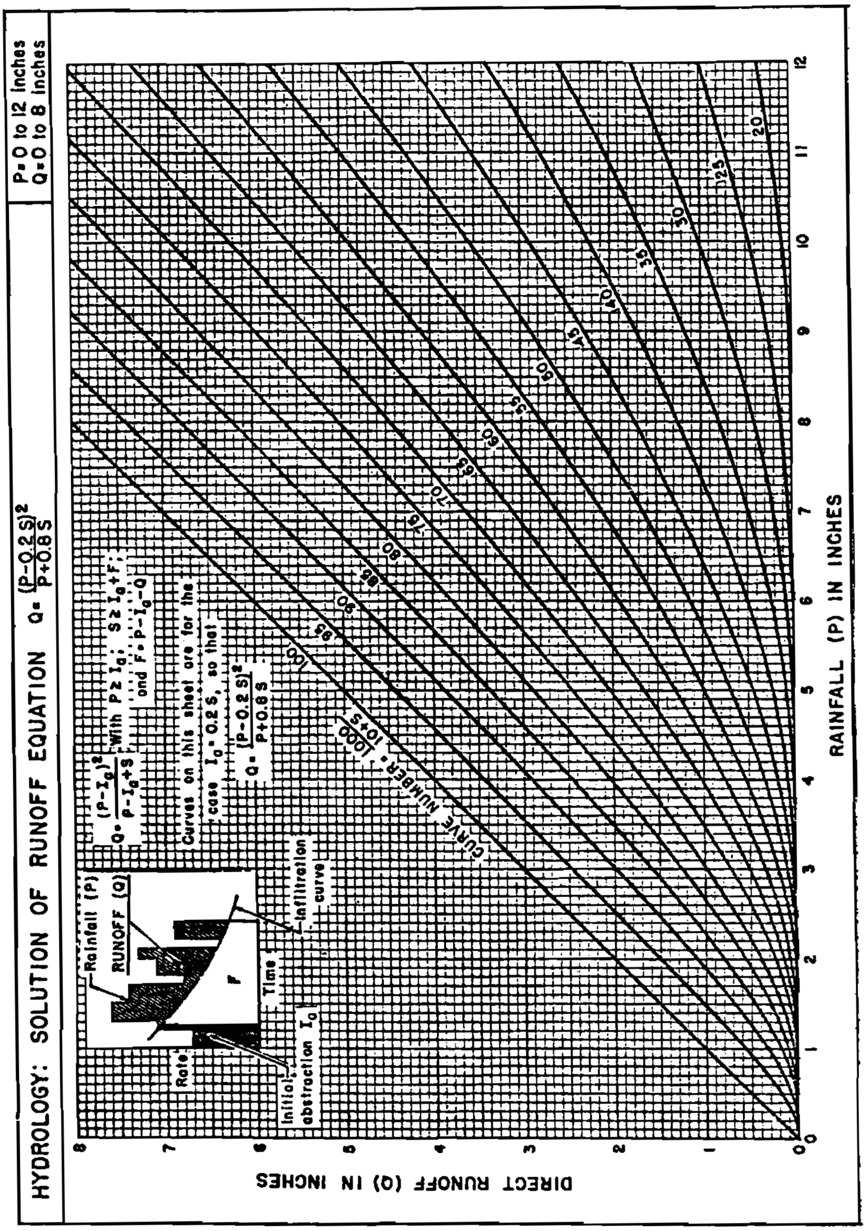

Figure 1. Soil Conservation Service curve number method of storm runoff estimation (15).

The peak rate of runoff, q_p, (required in the erosion model) is estimated by the empirical relationship (14)

$$q_p = 200\ D^{0.7}\ C^{0.159}\ Q^{(0.917D^{0.0166})}\ L^{-0.187} \quad (3)$$

where D is drainage area, C is mainstem channel slope, Q is daily runoff volume, and L is the watershed length-width ratio. Although Eq. (3) was developed and tested for basin-sized areas, testing of CREAMS has shown it to be applicable for field-sized areas as well.

Option 2: The infiltration model is based on the Green and Ampt equation (8, 13). The concept defined in Figure 2 assumes some soil water initially in a surface infiltration-control layer. When rainfall begins, the soil water content in the control layer approaches saturation and surface ponding occurs at a time, t_p (Figure 2). The amount of rain that has infiltrated by the time of ponding, designated F_p in Figure 2, is analogous to initial abstraction in the SCS curve number model (Option 1) but is also a function of rainfall intensity. After the time of ponding, water is assumed to move downward as a sharply defined wetting front with a characteristic capillary tension as the principle driving force. The infiltration curve of Figure 2 is approximated to give the infiltrated depth ΔF in a time interval, Δt, as

$$\Delta F = [4A(GD + F) + (F - A)^2]^{1/2} + A - F, \quad (4)$$

where $A = K_{si} t_i / 2$, $D = \theta_s - \theta_i$, θ_s is water content at saturation, θ_i is initial water content, G is the effective capillary tension of the soil, and K_s is the effective saturated conductivity. The average infiltration rate

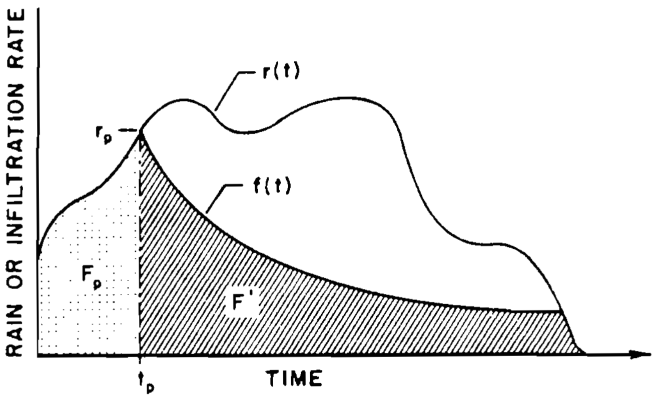

Figure 2. Schematic representation of runoff model using infiltration approach (13).

$\overline{f}_i$ for the ith interval is

$$\overline{f}_i = \frac{\Delta F_i}{\Delta t_i} \tag{5}$$

and runoff/rainfall excess q_i during the interval is rainfall rate for the interval minus the infiltration rate, $r_i - \overline{f}_i$. Total runoff is the sum of all q_i for the storm. The infiltration-based model has three parameters: G, D, and K_s.

Percolation is estimated as in Option 1, except that a single layer below the infiltration control layer represents the root zone. Percolation is calculated using average profile soil water content above field capacity and the saturated hydraulic conductivity, K_s. Peak rate of runoff is estimated by attenuating the rainfall excess using the kinematic wave model with parameter values to account for nonuniform steepness and roughness along the slope (18).

Evapotranspiration

The evapotranspiration (ET) element of the hydrology component is the same for both options. The ET model, developed by Ritchie (12), calculates soil and plant evaporation separately. Evaporation, based on heat flux, is a function of daily net solar radiation and mean daily temperature, which are interpolated from a Fourier series fitted to mean monthly radiation and temperature (10). Soil evaporation is calculated in two stages. In the first, soil evaporation is limited only by available energy and is equal to potential soil evaporation. In the second, evaporation depends on transmission of water through the soil profile to the surface and time since stage two began. Plant evaporation is computed as a function of soil evaporation and leaf area index. If soil water is limiting, plant evaporation is reduced by a fraction of the available soil water. Evapotranspiration is the sum of plant and soil evaporation but cannot exceed potential soil evaporation.

The Erosion Component

The erosion component considers the basic processes of soil detachment, transport, and deposition. The concepts of the model are that sediment load is controlled by the lesser of transport capacity or the amount of sediment available for transport. If sediment load is less than transport capacity, detachment by flow may occur, whereas deposition occurs if sediment load exceeds transport capacity. Raindrop impact is assumed to detach particles regardless of whether or not sediment is being detached or deposited by flow. The model represents a field comprehensively by considering overland flow over complex slope shapes, concentrated channel flow, and small impoundments or ponds (Figure 3). The model estimates the distribution of sediment particles transported as primary particles--sand, silt, and clay--and large and small aggregates which are conglomerates of primary particles. Sediment sorting during deposition and the consequent enrichment of the sediment in fine particles is calculated.

Detachment is described by a modification of the USLE for a single storm event (6). Rate of interrill detachment, D_{IR}, in the overland flow element is expressed as

$$D_{IR} = 0.210 \text{ EI } (S_{of} + 0.014) \text{ KCP}(q_p/Q), \qquad (6)$$

where EI is the product of a storm's energy and maximum 30-minute intensity, S_{of} is the slope of the land surface, q_p is peak runoff rate, Q is runoff volume, K is a soil erodibility factor, C is a cover-management factor, and P is a contouring factor. Rate of detachment, D_R, by rill erosion is expressed by

$$D_R = 37983 \text{ } nq_p^{4/3}(x/72.6)^{n-1} \, S_{of}^2 \text{ KCP} \qquad (7)$$

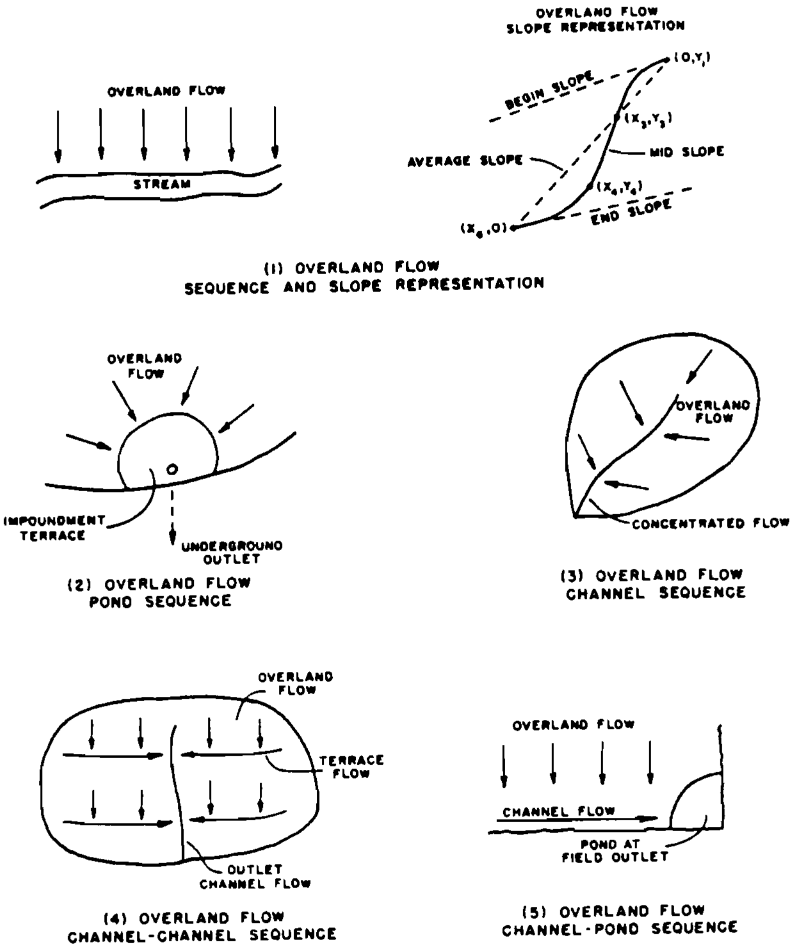

Figure 3. Schematic representation of typical field systems in the field-scale erosion/sediment yield model.

where x is the distance down slope and n is a slope-length exponent. The factors K, C, and P are from the USLE. Interrill erosion is primarily a function of raindrop impact on areas in between the rills and is not a function of runoff as the term q_p/Q suggests in Eq. 6. This term converts a total erosion amount for the storm to an average rate. Rill erosion is a function of runoff rate. Sediment transport capacity for overland flow is estimated by the Yalin transport equation (19) modified for nonuniform sediment having a mixture of sizes and densities.

The concentrated flow or channel element of the erosion model assumes that the peak runoff rate is the characteristic discharge for the channel. Calculation of detachment or deposition and transport of sediment are based on this discharge. Discharge is assumed to be steady, but spatially varied, increasing downstream from lateral inflow. Friction slope of the flow is estimated from regression equations fitted to solutions of the spatially varied flow equations so that drawdown or backwater from a control at the channel outlet can be considered.

Detachment can occur when sediment load is less than transport capacity of the flow and shear stress of the flow is greater than the critical shear stress for the soil in the channel. Both bare and grassed waterways, combinations of bare and grass channels, and variable slope along the channel can be considered.

Water is often impounded in fields, either as normal ponding from a restriction at a fence line, a road culvert, a natural pothole, or in an impoundment-type terrace. These restrictions reduce flow velocity, causing coarse-grained primary particles and aggregates to be deposited. Deposition depends on whether fall velocity of the particles causes the sediment to reach the impoundment bottom before flow carries them from the impoundment. The fraction of particles passing through the impoundment, FP, of a given particle class, i, is given by the exponential relation

$$FP_i = A_i e^{B_i d_i} \quad (8)$$

where d_i is the equivalent sand-grain diameter and A_i and B_i are coefficients that depend on impoundment geometry, inflow volume, infiltration through the impoundment boundary, and discharge rate from the impoundment.

In addition to calculating the sediment transport fraction for each of five particle classes, the model computes a sediment enrichment ratio, based on specific surface area of the sediment and organic matter and the specific surface area for the residual soil. As sediment is deposited, organic matter, clay, and silt are the principle particles transported, which results in high enrichment ratios. Enrichment ratios are important in transport of chemicals associated with sediment.

The Chemistry Component

Plant Nutrients

The basic concepts of the nutrient component are that nitrogen and phosphorus attached to soil particles are lost with sediment yield, soluble nitrogen and phosphorus are lost with surface runoff, and soil nitrate is lost by leaching from percolation, by denitrification, or by extraction by plants.

The nutrient component assumes that an arbitrary surface layer 10 mm deep is effective in chemical transfer to sediment and runoff. All broadcast fertilizer is added to the active surface layer, whereas only a fraction is added by fertilizer incorporated in the soil; the rest is added to the root zone. Nitrate in the rainfall contributes to the soluble nitrogen in the surface layer.

Soluble nitrogen and phosphorus are assumed to be thoroughly mixed with the soil water in the active surface layer. This includes soluble forms from the soil, surface-applied fertilizers, and plant residues. The imperfect extraction of these soluble nutrients by overland flow and infiltration is expressed by an empirical extraction coefficient. The amounts of nitrogen and phosphorus lost with sediment are functions of sediment yield, enrichment ratio, and the chemical concentration of the sediment phase.

When infiltrated rainfall saturates the active surface layer, soluble nitrogen moves into the root zone. Incorporated fertilizer, mineralization of organic matter, and soluble nitrogen in rainfall percolated through the active surface layer increase the nitrate content in the root zone. Uniform mixing of nitrate in soil water in the root zone is assumed. Mineralization is calculated by a first-order rate equation from the amount of potential mineralizable nitrogen, soil water content, and temperature. Optimum rates of mineralization occur at a soil temperature of 35°C. Soil temperature is approximated from air temperature in the hydrology component.

Nitrate is lost from the root zone by plant uptake, leaching, and denitrification. Plant uptake of nitrogen under ideal conditions is described by a normal probability curve. The potential uptake is reduced to an actual value by a ratio of actual plant evaporation to potential plant evaporation. A second option for estimating nitrogen uptake is based on plant growth and the plant's nitrogen content.

The amount of nitrate leached is a function of the amount of water percolated out of the root zone estimated by the hydrology component and the concentration of nitrate in the soil water. Denitrification occurs when the soil water content exceeds field capacity. The rate constant for denitrification is calculated from the soil's organic carbon content and is reduced by a twofold reduction for each 10-degree increase in temperature from 35°C.

Thus, the plant nutrient component estimates nitrogen and phosphorus losses in sediment, soluble nitrogen and phosphorus in the runoff, and changes in the soil's nitrate content due to mineralization, uptake by the crop, leaching by percolation through the root zone, and by denitrification in the root zone for each storm. Concentrations of nitrogen and phosphorus in the runoff and sediment are computed. Individual storm losses are accumulated for annual summaries which are also used to compute average concentrations.

Pesticides

The pesticide component estimates concentration of pesticides in runoff (water and sediment) and total mass carried from the field for each storm during the period of interest. The model accomodates up to ten pesticides simultaneously in a simulation period. Foliar-applied pesticides are considered separately from soil-applied pesticides, because degradation of pesticides is more rapid on foliage than in soil. The model considers multiple applications of the same chemical, like insecticides. A flow chart of the pesticide component is shown in Figure 4.

As in the plant nutrient component, an active surface layer is assumed that is about 1/2 inch deep. Movement of pesticides from the surface is a function of runoff, infiltration, and pesticide mobility parameters. Pesticide in runoff is partitioned between the solution phase and the sediment phase by the following relationships:

$$(C_w Q) + (C_s M) = a C_p \quad (9)$$

and

$$C_s = K_d C_w \quad (10)$$

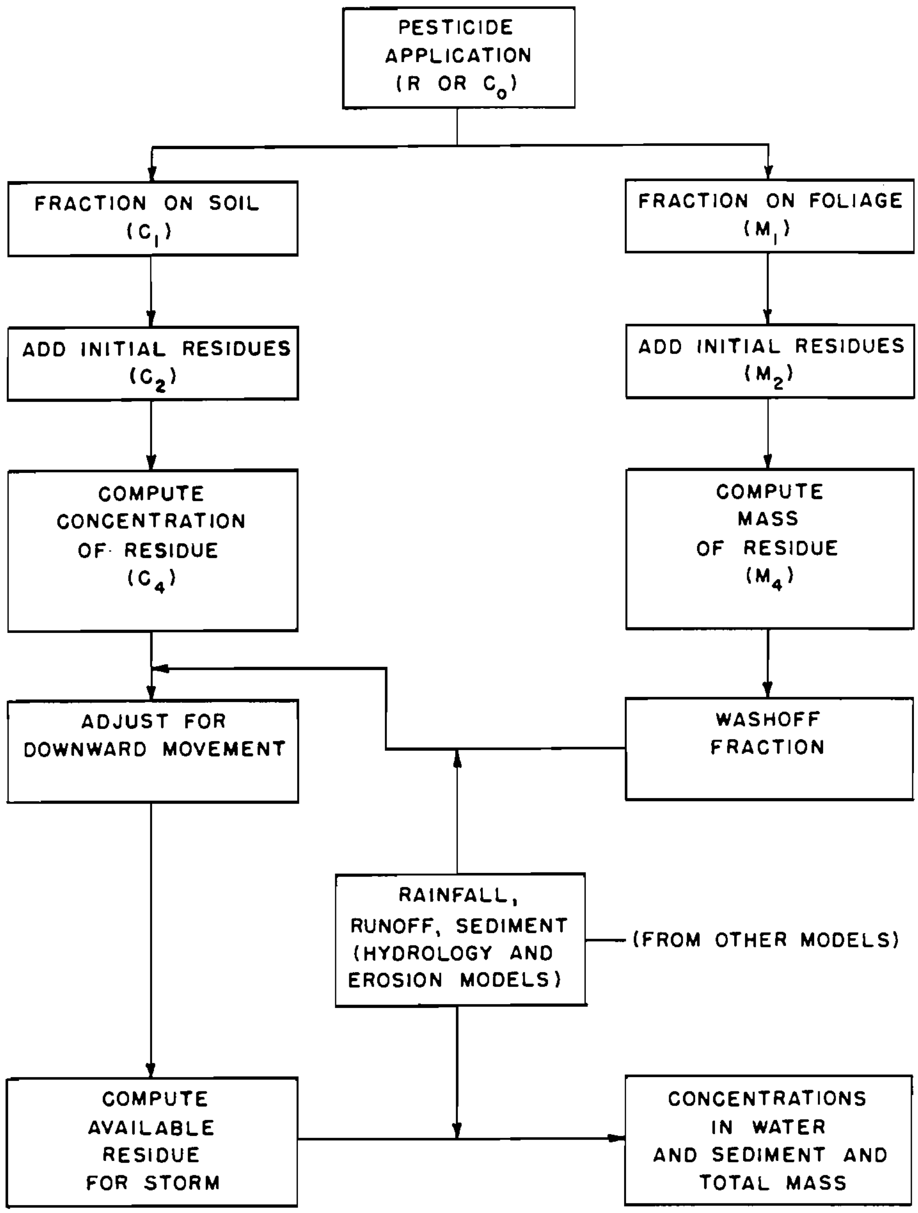

Figure 4. Simplified schematic representation of the pesticide model.

where C_w is pesticide concentration in runoff water, Q is volume of water per unit volume of surface active layer, C_s is pesticide concentration in sediment, M is mass of soil per unit volume of active surface layer, a is the extraction ratio of the concentration of pesticide extracted by runoff to the concentration of pesticide residue in the soil, C_p is the concentration of pesticide residue in the soil, and K_d is the coefficient for partitioning the pesticide between sediment and water phases. The concentration C_w of the pesticide in solution in runoff from the field is less than the soluble concentration in the surface layer because of inefficient extraction by runoff. The pesticide concentration C_s is that in the soil material of the surface layer. Selective deposition as expressed by enrichment ratio enriches this concentration in the sediment leaving the fields. The amount of pesticide attached to the sediment leaving the field is the product of the concentration C_s, sediment yield, and enrichment ratio.

Pesticide washed off foliage by rain increases the residual pesticide concentration in the soil. The amount calculated as available for washoff is updated between storms by a foliar degradation process. Pesticide residue in the surface layer is reduced by imperfect extractions by overland flow and infiltrated rainwater and by degradation described by an exponential function with a half life parameter.

MODEL APPLICABILITY

CREAMS was developed as a state-of-the art model to consider alternate practices, acceptable by farmers, to reduce nonpoint source pollution. The complex interaction of soils, topography, crops, tillage, chemical applications, and conservation practices, among others, are such that response from rainfall events is site specific. That is, pollution potential varies considerably from field to field within land resource areas and between land resource areas. However, CREAMS can be applied for generalized soils, topography, and cropping situations to estimate relative effects among management systems for farm planning purposes.

CREAMS is not a water quality model in that it does not estimate eutrophication or toxicity for water bodies. The output from the model re represents estimates of sediment and chemical loads at the edge or outlet of a field. Routing of pollutant loads through channel systems is not included in the model. Therefore, the model cannot be applied to a situation of combined fields with an interconnecting channel system. Channel systems in small watersheds or basins may be dominating factors in the delivery of sediment and chemicals to receiving waters. Appropriate routing techniques would be needed to move the pollutant loads generated by CREAMS.

In addition to farm field applications of CREAMS, the model is currently being applied on strip mine areas and sanitary landfill sites. Application on strip mine sites is made to plan conservation practices for control of erosion and chemical losses. Application on sanitary landfills is concerned with percolate-water leaching of chemicals. Combinations of agronomic and compaction practices that affect the water balance components, including percolation, are significant in chemical leaching. Although data are not available for testing CREAMS on landfill sites, if soil parameter values can be estimated realistically, the model should provide realistic results.

Limited application of CREAMS has been made on radioactive waste disposal sites. Design of runoff and erosion control practices can be made to minimize losses of both adsorbed and dissolved chemicals from disposal areas.

The hydrology and erosion components of CREAMS has been tested on pasture-rangeland watersheds with varying results. The major difficulty encountered in such an application is adequate representation of leaf area index (LAI) values for different species of grasses. Forage utilization by livestock is difficult to estimate, and in turn, the reduced LAI resulting from grazing. Mixtures of different species of both cool and warm season grasses in the same pasture cause difficulty in adequately estimating LAI. Also, such mixtures cause selective grazing by livestock which can result in nonuniform forage utilization. Brush species oftentimes associated with rangelands are difficult to represent in application of CREAMS. Rooting and water use characteristics are different for grasses and brush. Preliminary testing of the CREAMS hydrology component on wooded watersheds indicate that some adjustment is needed in the evapotranspiration component to adequately reflect soil evaporation and plant transpiration for a tree canopy with significantly greater LAI than for agricultural crops.

Nutrient cycling on pasture/rangeland applications of CREAMS is not adequate to consider effects of alternate grazing systems. Nonuniform application of animal waste, selective foraging by livestock, and the various nutrient transformations result in extreme difficulty in applying the model.

Variability of rainfall from year to year and distribution of rainfall within a year are such that results of any model application are climate dependent. The occurrence or nonoccurrence of runoff producing storms during high erosion-potential periods, or shortly after application of fertilizers and pesticides, may be critical in any particular year. Evaluation of nonpoint source pollution from alternate management practices should not be made for a single year, or even two or three years. CREAMS was designed to be computer efficient such that a 20-year period of simulation could be made at a relatively low cost. Such a record length would include both wet and dry years with different distributions within the years. Results from a 20-year simulation are much more meaningful and more confidence can be gained. The design or selection of management systems for nonpoint source pollution control may need to be based on risk analysis, particularly potentially toxic pesticide losses. That is, how many occurrences exceed some predetermined pesticide concentration or load during a time period. Such a risk analysis must be made with relatively long-term simulation such as a 20-year record. If some toxic level is exceeded only once in the 20 years, some economic value can be placed on the associated risk. This type of analysis should be considered when economics enter into the decision making process. Costly control measures may not be justified if a toxic condition results on the average of only once in 20 years or once in 50 years. On the other hand, a once in 10 year exceedance may justify considerable expenditures on extreme conservation measures. Another reason for long-term simulation is to effectively consider crop rotations. Due to rainfall variability, several years, or cycles, of the rotation must be simulated such that each crop of the rotation potentially can be represented in wet and dry years. For example, a 4-year rotation must be run for absolute minimum 12-year simulation period. Each crop will appear only three times during the simulation period.

Components of the CREAMS model were tested with data from as many locations as possible with varying degrees of results. However, there are limitations on applicability that have not been determined adequately. For example, runoff volume estimates should be valid for a wide range of field sizes from a fraction acre to 200 acres or more. However, the estimate of peak rates of runoff for erosion/sediment yield calculation may not be valid for very small areas such as a 1/4 acre plot. Peak rates for long narrow fields with length-to-width ratios greater than 4 may not be realistic when considering overland flow with channels or impoundments. The peak rates may be valid for runoff, but may not provide good characterization for erosion/sediment transport. Fields for which large length-width ratios exist generally represent conditions that require flow routing techniques not included in CREAMS. Extremely steep slopes have not been tested adequately for CREAMS application. Slopes in excess of 20 percent with little or no cover and surface roughness may have near critical flow conditions. It is doubtful that estimates of peak rates would be valid for these conditions.

CREAMS has not been tested on irrigated fields, although normal application has been made for sprinkler irrigation with realistic results. Such an application with excess irrigation resulting in runoff should be feasible. However, flood or row irrigation with water in excess of soil water deficiency would not give realistic response. There would not be raindrop detachment of soil particles and erosion might occur due to shear stress from flowing water. The erosion component of CREAMS assumes spatially varied uniformly increasing discharge for erosion/deposition in concentrated flow. Flood or row irrigation involves decreasing flow rate resulting in a different energy gradient.

In climatic regions where rainfall may occur on snow or on frozen ground, estimated runoff volumes probably are grossly underestimated. Preliminary testing has been made in the northwest United States where frozen soil occurred below a very shallow unfrozen layer when significant rainfall events were experienced. Large volumes of runoff were observed when little or none was simulated. Significant runoff may result in erosion of the unfrozen top layer largely as a sheet. This is especially true for steeply sloping areas. The hydrology component of CREAMS does not adequately consider frozen ground. A revision can be made based upon the air temperature, but this alone is not sufficient to treat the above mentioned condition of an unfrozen layer overlying a frozen zone. This would require an extensive subroutine to consider heat flux and insolation and their interactions.

At latitudes greater than 60^{o}, monthly radiation values plot approximately triangular in shape. That is, there is very little radiation during winter months, but it increases rapidly to a peak summer value and decreases just as rapidly following the peak. The fourier function used to fit the data does not adequately describe the shape and negative values result during the winter period. A constraint was programmed into the model to prevent negative values, but the fourier function cannot adequately represent the steep triangular shape. However, sensitivity analysis showed that runoff and percolation estimates are not very sensitive to large changes in leaf area index as calculated from radiation. Therefore, results of CREAMS application are not too adversely affected, especially when considering relative differences between management practices.

Despite some limitations and shortcomings of the CREAMS model, it is a useful tool for evaluating nonpoint source pollution. Since the model is very computer efficient, the model has other potential uses for examining long-term trends. The most significant use of the model is for analysis of relative differences between different management practices.

APPLICATION

A major utility of CREAMS is evaluation of alternate management practices for control or minimization of runoff of sediment and chemicals. Several alternate practices might be proposed for a given site. Each could be evaluated with CREAMS, and the farmer could select a practice best suited to his needs from those judged to be satisfactory.

Example Area and Practices

Application of CREAMS is illustrated for a 3.2-acre area from the Georgia Piedmont physiographic area. Figure 5 shows the topography of the field. The fence line restricts surface drainage, which results in temporary ponding of runoff. The soil is a Cecil sandy loam having a depth of 24 inches to the B2 horizon. Five management practices are analyzed for continuous corn.

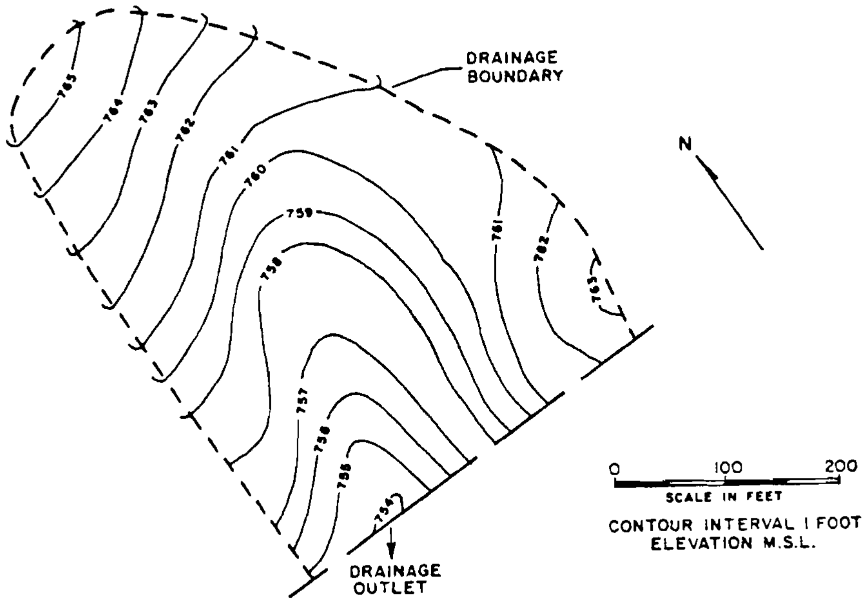

Figure 5. Topographic map for the Georgia Piedmont field

Practice 1. Conventional tillage--moldboard plow in the spring, disk twice, plant, and cultivate twice. Rows run across the drainage, more or less on the contour in the upper end of the field and generally up and down slope at the lower end. Runoff is restricted at the fence line.

Practice 2. Same as practice 1, except with a grassed waterway in the concentrated-flow area.

Practice 3. Chisel plow is used instead of moldboard, and no cultivation; grassed waterway is used in the concentrated-flow area.

Practice 4. Conventional tillage, same as practice 1, channel-type terraces with 0.2 percent grade, tillage on contour, grassed terrace outlet channel.

Practice 5. Same as practice 1, with a tile outlet impoundment at the fence line.

The plant nutrient component was run twice, once with practice 1 for a single application of 140 kg/ha nitrogen and 28 kg/ha phosphorus at planting time and again with a split application of nitrogen: 25 kg/ha incorporated at planting time and 112 kg/ha topdressed 40 days after planting. A soluble pesticide, atrazine, and one adsorbed type, paraquat, were assumed to be surface applied at planting time at the rate of 3.36 kg/ha and 2.05 kg/ha, respectively, for each of the management practices. Paraquat used in this application is considered only as an indicator for transport of any strongly soil adsorbed chemical that is applied annually or is present as a residue from previous applications.

Results from Hydrology Component

The daily rainfall hydrology option was used to generate hydrologic values required by the erosion and chemistry components. The results are shown in Table 1. Hydrologically, the only changes are in management practices 3 and 4

Table 1. Hydrologic analysis of several farming practices for the example Georgia watershed. Values are from CREAMS simulations.

Management practice	Rainfall[a]	Runoff	Percolation	Evapotranspiration	Product[b] $Q \cdot q_p$	
					(total)	average per event
	(mm)	(mm)	(mm)	(mm)	(mm^2/hr)	(mm^2/hr)
	2946	366	617	1991	24968	480
2	2946	366	617	1991	24968	480
3	2946	226	742	2002	14258	396
4	2946	226	742	2002	12710	3535
5	2946	368	620	1991	24968	480

[a]Total for the period May, 1973 - October, 1975.

[b]Product of runoff volume, Q, and runoff peak rate, q_p.

as compared with practice 1. Reduced curve numbers resulted in less computed runoff for these two practices. The roughness and the surface cover of corn residue in the chisel plow system accounts for its reduction in runoff. In practice 4, the terraces and contouring reduce runoff volume and attenuate the peak rate of runoff because of a longer total flow path (increased effective length:width ratio). The parameters were not chosen to reflect a hydrologic influence of the grassed waterway or impoundment at the fence line.

The effect of terraces and contouring on runoff was equivalent to that of chiseling and associated crop residue. Runoff volume, and thus percolation and evapotranspiration, did not change between practices 3 and 4. Runoff, percolation, and evapotranspiration are the same for practices 1, 2, and 5. However, runoff from these practices was 1.6 times that from practices 3 and 4.

The last column of Table 1 gives the sum of the product of volume of runoff and peak runoff rate for the period of record which is an index of the potential power of runoff for sediment transport. The index provides a relative comparison of the management practices. Since runoff volumes and peak rates did not change between practices 1, 2, and 5, the index value did not change.

The peaks associated with lower volumes for practice 3 resulted in a much lower value, and the peak attenuation caused by the terraces in practice 4 further reduced the index even though volumes were the same for practices 3 and 4. The empirical relationship for peak rate (Equation 3) does not reflect an increased hydraulic roughness for grassed waterways such as in practice 2 or the effect of impoundments such as in practice 5.

Results from Erosion/Sediment Yield Component

To apply the erosion component, an overland flow element and a concentrated flow element were used to represent the watershed for practices 1, 2, and 3. An impoundment element was added for practice 5. Practice 4 was represented by an overland flow element and a series of two channel elements. Parameter values for 10 overland flow paths around the watershed were averaged for a representative overland flow path. The fence line at the watershed outlet was assumed to restrict flow causing backwater.

Simulation results shown in Table 2 indicate the factors affecting erosion and sediment yield at this site. Deposition occurred with practice 1 since the enrichment ratio, ER, of 2.1 is greater than 1.0. If the model computes no deposition, ER is 1.0. Deposition was on the toe of the concave overland flow slope, but most was in backwater immediately above the fence line. The model predicted that the natural waterway upstream from the backwater would erode.

A grassed waterway, practice 2, eliminated erosion by concentrated flow in the previously unprotected waterway and caused deposition of some of the sediment eroded on the overland flow area. The increase in ER from 2.1 to 2.7 resulted from increased deposition. Fines were not reduced in the same proportion as sediment yield (SY) because the ER increased. The product of SY and ER, a relative measure of both sediment yield and specific surface area, indicates the carrying capacity for chemicals attached to the sediment.

Deposition in and at the edges of the grassed waterway would cause maintenance problems and should be reduced by reducing erosion on the overland flow area. The chisel plow conservation tillage system, practice 3, provided that reduction, which would also help to maintain soil productivity.

Instead of conservation tillage, the farmer may prefer conventional tillage with conventional terraces, practice 4, and a grassed outlet channel. sediment yield was reduced by 82 percent, but ER increased because of considerable deposition in the terrace channels and in the grassed outlet channel. Another possibility was an impoundment terrace, practice 5, which further reduced sediment yield, but greatly increased ER. The resulting SY·ER was as high as that for practice 3 where SY was 1.8 times that of practice 5.

Table 2. Erosion/sediment yield analysis of several farming practices for the example Georgia watershed. Values are from CREAMS simulations.

Management Practice	Sediment Yield[a/] (SY)	Enrichment ratio (ER) based on specific surface area	Product SY·ER
	t/ha)		t/ha
1	10.61	2.1	22.28
2	5.38	2.7	14.53
3	2.00	2.3	4.60
4	1.93	2.9	5.60
5	1.08	4.3	4.64

[a/]Total for the period May, 1973 - October, 1975.

As expected, enrichment ratio increased as sediment yield decreased, but in a scattered fashion. Furthermore, the relationship may be quite different for other sites.

Results from Nutrient Component

Results from the plant nutrient component are summarized in Table 3 where total nitrogen and phosphorus losses for the 30-month period are given. Two runs were made for management practice 1 to demonstrate the effects of possible fertilizer treatments. Fertilizer application was the same for management practices 1A, 2, 3, 4, and 5, where 28 kg/ha of nitrogen was incorporated at planting time, and 112 kg/ha of nitrogen was topdressed approximately 30 days after corn emergence. In practice 1B, the total 140 kg/ha of nitrogen was incorporated at planting time.

The results for practices 1A, 2, 3, 4, and 5 reflect differences caused by changes in runoff and sediment yield for the different practices. Practices 3 and 4 resulted in less runoff and more percolation than in practices 1A, 3, and 5. Thus, the nitrogen and phosphorus in runoff was less for practices 3 and 4, but more nitrate was leached out of the root zone and more denitrification occurred. Plant uptake of nitrogen changed very little since there was little change in ET. These changes in nitrogen uptake reflect slightly different crop yield due to differences in water and nitrogen availability.

Split application versus single application of nitrogen can be evaluated by comparing results for practices 1A and 1B. Part of the difference in nitrogen loss is due to storm rainfall/runoff/sediment loss events relative to time of application, and part is due to all of the nitrogen being incorporated in the soil for practice 1B. Nitrogen uptake was less for the single application than for the split application for the same ET because leaching and denitrification depleted the high soil nitrate following single application. This illustrates the influence of storm sequence. If rainfall had been more frequent, but less in total amount, the results might have been entirely different. Nitrate leaching among the 5 practices reflects the change in percolation. Surface losses of nitrogen and phosphorus largely reflect runoff and sediment losses.

Results from Pesticide Component

Pesticide losses for the five management practices are summarized in Table 4 for the simulation period. Atrazine and paraquat represent a dissolved and a sediment-attached pesticide, respectively, and the losses show the effects of

Table 3. Summaries of total plant nutrient components for five management practices for the Georgia Piedmont, 1973-75. Values are from CREAMS simulations.

	Management Practice					
	1A[a]	1B	2	3	4	5
Nitrogen (kg/ha)						
Inputs						
Fertilizer	420.0	420.0	420.0	420.0	420.0	420.0
Rainfall	23.6	23.6	23.6	23.6	23,6	23.6
Mineralization	72.8	72.8	72.8	73.1	73.1	/3.8
Outputs						
Runoff	3.7	3.4	3.7	2.1	2.1	3.7
Sediment	37.7	37.7	22.1	9.1	8.7	5.4
Plant uptake	322.1	220.0	322.1	319.9	319.9	322.1
Leaching	58.1	106.3	58.1	68.5	68.5	58.1
Denitrification	107.3	204.6	107.3	102.6	102.6	107.3
Phosphorus (kg/ha)						
Inputs						
Fertilizer	84.0		84.0	84.0	84.0	84.0
Outputs						
Runoff	1.34		1.34	.78	.78	1.34
Sediment	14.3		8.3	3.4	3.2	2.0

[a] Practices 1A, 2, 3, 4, and 5 had 28 kg/ha of nitrogen fertilizer incorporated at planting and a topdressing of 112 kg/ha approximately 30 days after corn emergence. Practice 1B had 140 kg/ha incorporated at planting time.

the management practices on runoff and erosion. Atrazine is transported mainly in water, and the reduced runoff from chisel plowing and terracing (practices 3 and 4, Table 1) reduced losses by about 80 percent. The slight changes in loss from practices 1 to 2 to 4 reflect the small amount of atrazine transported by sediment. Since paraquat is transported mainly in sediment, losses are generally closely associated with sediment yield. The exception is for practice 5, where the impoundment resulted in the lowest sediment yield (Table 2). Deposition of coarse particles in the impoundment resulted in the highest enrichment ratio, and sediment having the highest fraction of fines. The fine sediment is the main carrier of pesticides attached to sediment. Enrichment of fines resulted in more paraquat loss from practice 5, the impoundment system, than from practice 3, the chisel plow system, where sediment yield was greater.

Utility of Results

The relative results of application of the CREAMS model may not occur for the same practices in other land resource areas or other fields in the same land resource area. Application of the model is site specific, and the examples represent a specific topographic and climatic situation. However, these results demonstrate the utility of CREAMS as a tool to evaluate alternate management practices and the complex interactions among the components for the several practices. The results show that a specific management system may not minimize all pollutants (sediment, plant nutrients, and pesticides). Factors other than minimizing pollutants must be considered in selecting a management practice, such as farm machinery requirements and the farmer's economic constraints.

Table 4. Summary of total pesticide losses for five management practices on the example Georgia watershed, 1973 to 1975. Values are from CREAMS simulations.

Management practice	Pesticide					
	Atrazine			Paraquat		
	Total applied (kg/ha)	Total loss (kg/ha)	Percent of application	Total applied (kg/ha)	Total loss (kg/ha)	Percent of application
1	10.0	0.055	0.55	6.2	0.265	4.32
2	10.0	.048	.54	6.2	.151	2.46
3	10.0	.022	.22	6.2	.039	0.65
4	10.0	.022	.22	6.2	.063	1.03
5	10.0	.053	.53	6.2	.054	0.88

SUMMARY

Mathematical models to assess nonpoint source pollution and evaluate effects of management practices for its control are needed to adequately respond to Water Quality Legistlation of the past 10 years. Consequently, the U.S. Department of Agriculture, Science and Education Administration, Agricultural Research, has developed CREAMS, a field scale model for Chemicals, Runoff, and Erosion from Agriculture Management Systems. The model includes components for

hydrology, erosion/sediment yield, and chemical transport that describe the movement of runoff, sediment and its characteristics, plant nutrients, and pesticides from field sized areas. It is a continuous simulation model that operates efficiently to allow consideration of long records (20 years). The utility of the model is evaluation of alternate management practices for their impact on the yield of sediment and chemical pollutants from field-sized areas at specific sites. A number of alternate practices can be proposed for a site, and after evaluation of each with CREAMS, a practice could be chosen from those judged to adequately control sediment and chemical yield on the basis of results from CREAMS.

ACKNOWLEDGEMENTS

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P A R T II

CASE STUDIES

- o FINLAND
- o F.R.G.
- o POLAND
- o SWEDEN
- o U.K.
- o U.S.S.R.

TESTING THE APPLICATION OF CREAMS TO FINNISH CONDITIONS

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INTRODUCTION

Non-point source pollution of water courses, especially agricultural, has received much attention during recent years due to the fact that treatment of sewage and industrial effluents has become more efficient. For this reason it has become more important to be able to estimate loads from non-point sources accurately and to investigate means of reducing these loads. The applicability of CREAMS for these purposes was tested.

THE HOVI BASIN CASE STUDY

The model was tested with data from the totally agricultural Hovi basin, situated in Vihti, about 30 kilometers west of Helsinki. The data chosen for calibration were from the years 1968-1969, when a special investigation with frequent sampling was carried out. The area of the Hovi basin is 12.0 hectares and during the years 1968-1969 it was entirely open-ditched. The mean slope of the basin is 2.8% and the particle-size distribution of the soil is 55% clay, 43% silt and 2% sand, which is a clay loam.

In 1968 the crop consisted of wheat (2.3 hectares), oats (4.3 hectares) and barley (3.3 hectares). Fertilizers applied (5.5.1968) were 26 kg/ha nitrogen and 15 kg/ha phosphorus calculated per total area. In 1969 the crop consisted mainly of oats (5.6 hectares) with some barley (2.7 hectares) and wheat (1.0 hectares). The amount of nutrients applied (19.5.1969) were 32 kg/ha nitrogen and 16 kg/ha phosphorus. The nutrients were mixed into the top 10 cm of soil.

SELECTION OF PARAMETER VALUES

Monthly mean temperatures and radiation were calculated from daily observations of the Vihti meteorological station. Daily precipitation values were obtained from the same source. Because Option 1 did not include snow accumulation and snowmelt, the input precipitation data had to be modified. Precipitation between December 1, 1967 and March 20, 1968, and that between December 1, 1968 and April 10, 1969 was summed. The total precipitation thus obtained was then divided equally among the dates between March 21 and April 4, 1968, and April 11 and April 30, 1969 respectively. This selection of dates was based on the available daily temperature data. Although the method described above was very approximate, it was the only possibility of taking the winter conditions into account, because of a lack of time.

Direct measurements of many soil characteristics were missing. Parameter values needed by the hydrology submodel were estimated on the basis of measurements made in experimental fields in Vihti near the Hovi basin (Seuna, 1977) and on the basis of information given in the model manual. Soluble and total nutrient contents of the soil were mainly estimated on the basis of studies by Hartikainen (1978 and 1979). Option 2 was used for simulating nitrogen uptake.

For the sake of simplicity the basin was regarded as a uniform overland flow element because information on parameter values needed by the other elements was almost totally lacking. The parameter values of the erosion/sediment yield model were selected according to the model manual, and default values were used for many parameters.

RESULTS

Hydrology

Observations on runoff measured in the Hovi basin in fact represent combined runoff and percolation. Therefore, when comparing the observations with the calculated values, runoff and percolation calculated by the model had to be summed. Calculated and observed values corresponded rather well on a monthly and annual basis (Table 1). In 1968 the total runoff plus percolation observed was 265 mm and the corresponding value calculated by the model was 288 mm. In 1969 the values were 223 mm (observed) and 229 mm (calculated). On a daily basis, the timing of runoff was not successful, because according to the model the runoff response followed on the same day that the rainfall occurred, whereas in reality the response was observed on the day after the rainfall, due to the open-ditch drainage system.

Erosion/sediment Yield

Soil losses are not a common problem in Finland, unlike many other countries where prevention of erosion has been the most important criterion in choosing the best agricultural management practices. For this reason no direct observations on soil losses in Finland are available, but only estimates based on suspended solids concentrations in runoff waters.

In 1968 the average soil loss calculated by the model was 110 tons/km^2.a and in 1969, 88 tons/km^2.a. As calculated from the suspended solids concentrations in runoff waters the values of 14 tons/km^2.a for 1968 and 24 tons/km^2.a for 1969 were obtained.

Nutrient Losses

Nitrogen and phosphorus losses calculated by the model were significantly greater than those calculated from concentration and runoff observations (Table 2). Particularly in autumn, the model gave very high nutrient losses.

Table 1. Observed and calculated values of monthly runoff plus percolation in 1968 and 1969 in the Hovi basin, southern Finland

Month	Runoff + percolation (mm)			
	1968		1969	
	Observed	Calculated	Observed	Calculated
January	0	0	0	0
February	0	0	0	0
March	112.3	107.4	0	0
April	59.9	49.5	139.7	108.5
May	4.8	21.8	0.8	0.5
June	0.3	1.0	0	0
July	0.3	2.0	0	0.3
August	1.8	15.7	0	0
September	26.7	25.1	0.5	16.8
October	17.5	27.7	9.4	21.3
November	41.1	38.6	72.1	81.8
December	0	0	0	0
Total	264.7	288.2	222.5	229.2

It is difficult to say which of the values are correct, because the observations were not frequent enough. Furthermore, parameter estimation would require data on the nitrogen and phosphorus contents of the soil, which were not available at the time of calibration.

APPLICABILITY OF CREAMS TO FINNISH CONDITIONS

The hydrological part of the model is greatly defective when applied to Finnish conditions: Option 1 which was used, does not include winter conditions, i.e., snow and frost. However, using a simple and crude modification of the input precipitation data, satisfactory results were in fact obtained. It therefore seems quite probable that after the incorporation of a snowmelt sub-model in CREAMS, the hydrological part would work very well for Finnish conditions. This will be one of the most important tasks in the near future.

Table 2. Observed and calculated nitrogen and phosphorus losses in 1968 and 1969 in the Hovi basin, southern Finland

Month		Loss of nitrogen ($kg\ km^{-2}\ month^{-1}$)		Loss of phosphorus ($kg\ km^{-2}\ month^{-1}$)	
		Observed	Calculated	Observed	Calculated
1968	January	0.0	0.0	0.0	0.0
	February	0.30	0.0	0.0	0.0
	March	150.0	130.0	14.0	1.8
	April	420.0	270.0	19.0	23.0
	May	7.4	410.0	0.38	37.0
	June	0.16	39.0	0.01	4.0
	July	0.20	41.0	0.03	4.2
	August	2.9	360.0	0.71	37.0
	September	29.0	420.0	6.4	48.0
	October	33.0	360.0	3.9	24.0
	November	100.0	22.0	10.0	0.0
	December	1.4	0.0	0.09	0.0
1969	January	0.0	0.0	0.0	0.0
	February	0.0	0.0	0.0	0.0
	March	0.07	0.0	0.01	0.0
	April	870.0	230.0	62.0	23.0
	May	0.84	0.0	0.06	0.0
	June	0.06	0.0	0.01	0.0
	July	0.0	0.0	0.0	0.0
	August	0.0	0.0	0.0	0.0
	September	0.41	600.0	0.05	61.0
	October	26.0	800.0	0.64	80.0
	November	390.0	1300.0	17.0	140.0
	December	2.3	0.0	0.14	0.0

The calibration of the erosion/sediment model could not be carried out because of the lack of observations. However, the calculated values seem very reasonable compared with e.g., the American values. This is in agreement with the known low levels of erosion in Finland. Observations should be made to confirm these results.

In the case of nutrient losses the calibration was not very successful. This may, however, be due to the selection of parameter values. In particular, the nutrient content of the soil should be measured in the basin, because it can vary very much even between different basins situated near each other. With the aid of these measurements, the nutrient model may be tested more accurately.

To summarize, the CREAMS model seems to be potentially promising as a model for estimation of agricultural pollution in Finnish conditions. Its use is, however, restricted to the field scale. In water protection planning it is often important to be able to estimate non-point source loads on a drainage basin scale, and models suitable for this purpose should also be tested.

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ENVIRONMENTAL EFFECTS OF NITROGEN FERTILIZATION EXEMPLIFIED BY GROUNDWATER POLLUTION AS SIMULATED BY CREAMS

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INTRODUCTION

The increase of crop yield observed within the last few decades would hardly have been possible without the increased application of mineral fertilizers. Their role is therefore important in order to ensure sufficient food production for a constantly growing world population. In the Federal Republic of Germany this increasing fertilizer application was especially apparent for nitrogen fertilizer. Thus the consumption of nitrogen fertilizers in agriculture increased by 83 kg/ha to 126 kg/ha between 1960/61 and 1980/81 (Statistisches Bundesamt Wiesbaden). This development, however, is apparently accompanied by a considerable overloading of the environment, which is detrimental to the quality of some of our limited vital resources, e.g., food, soil and water. The most significant effect in the Federal Republic of Germany is that concerning ground- and surface-water, especially the decreasing quality of groundwater caused by nitrates which results in increasing problems with drinking water supplies. The resulting conflict which is becoming more and more important in the eyes of the public, raises the following question: How great a burden can the environment take and still remain productive, economically speaking, if economic and ecological aspects are considered. Answering this question requires, as a first step, the quantification of the relationship between agricultural fertilization and its external effects, which is given in this paper for groundwater pollution caused by nitrates, as this must be viewed as the macro-economically most significant by-product of high fertilization rates.

This relationship has to be quantified with the CREAMS model, as there is only little empirical data available. The empirical data especially do not allow a differentiation between various crops or crop rotations. Besides, the CREAMS model has the advantage of being able to reflect changes in nitrate pollution of groundwaters, due to different fertilization practices. First, however, the reliability of the model's results for conditions in the FRG had to be tested. The model will only be used to estimate nitrate leaching into groundwater and therefore the calibration of the model was done only for this aspect. Simulations of the erosion submodel will not be carried out.

DESCRIPTION OF THE CONTROL AREA

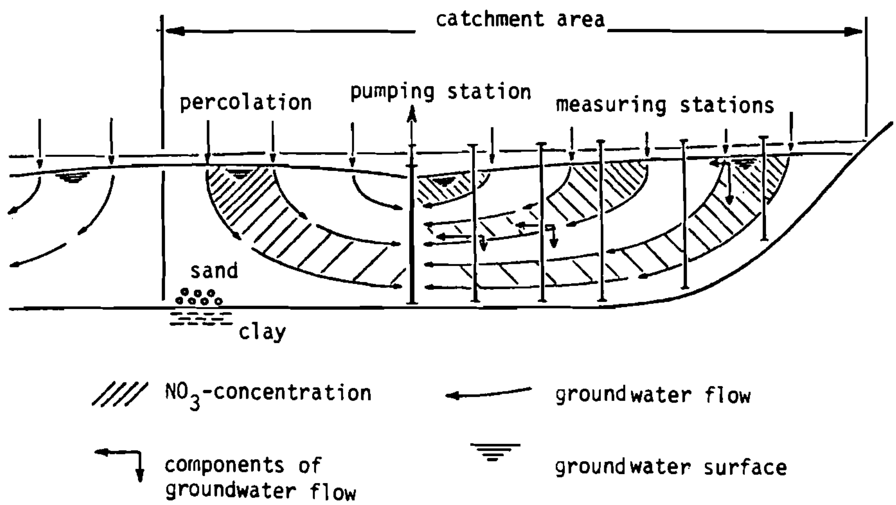
To calibrate the CREAMS model, the experimental data of the Mussum water reserve area was used. This area was chosen, first, because there are quite detailed measurements of the nitrate concentrations in groundwater as well as data concerning fertilization, cropping patterns, climatic, geological and hydrological conditions available; second, this area seems to represent quite well the kind of agricultural regions, which could be identified as "problem-areas" in the FRG, as there is rather intensive agricultural production on light sandy soils with a high leaching potential.

Mussum is located in the Northwestern part of Germany, close to the border with the Netherlands. The morphology of the catchment area is mainly plain, with only a few widely spread farms. 205 ha or 50% of the area is arable land, 145 ha or 35.4% is grassland, 5 ha or 1.2% is forest, and 13% roads, settlements and gardens. With an annual precipitation in the range of 700 to 750 mm and an average annual temperature of 9.3 degrees C (1.5° in January and 17.5° in July), the climatic conditions show no important differences in comparison to other low lying areas in West Germany. The summers are moderately warm, the winters are mild and precipitation is almost uniformly distributed over the whole year.

The geological formation of the main part of the catchment area is mainly fine, medium and coarse grained sands and grail covered by moderately deep gley-soils, podsol-gley soils, brown soils, gley-brown-soils and so-called 'Plaggenesch' sand soils with humus. The aquifer can be described as a porous water-bearing stratum with a vastly free groundwater table of pleistocene grails and sands. The seam thickness of the water yielding stratum ranges from about 10 to 15 m. The substratum of the aquifer are miocene silty clays. Above the aquifer is a waterless stratum of pleistocene fine and medium grained sands. The groundwater regeneration averages about 1.23 million m^3 for the whole area of approximately 4.1 km^2.

The whole catchment area can be easily outlined horizontally and vertically against the surroundings. A diagram of the groundwater flow is given in Figure 1.

Figure 1. The principle behind the groundwater flow to the water pumping station in the Mussum water reserve area.



THE HYDROLOGY SUBMODEL

Problems in Adjusting the Model

Referring to the users' manual, the model documentation and several other publications about the CREAMS model (Knisel, 1980), a model description is dispensible for this paper.

As there were only daily values of precipitation available, the first option of the hydrology submodel was applied. The precipitation data as well as data about temperature and radiation was used from the Bocholt meteorological station which is located only 6 km south of the research area. There was also quite detailed information available about the range of some of the other input parameters requested in Option 1 of the model, as a lot of research work had already been done in the Mussum water reserve after the water-pumping station had to be closed because of high nitrate concentration in the water supplied in 1970. The values of the input parameters used for the simulations of leaching from arable land, which were mostly gained by measurement or from personal information supplied by geologists and soil scientists (Sunkel 1975, 1979; Obermann 1977; Bundermann 1978) who had been working in this area, are listed in Table 1.

Table 1. Input parameters of the hydrology submodel (Option 1).

Symbol	Definition	Dimension	Values for Mussum
DACRE	Field area	acre	75.0
RC	Saturated hydrologic conductivity	in/hr	9.02
FUL	Field capacity/ upper limit of storage		0.48
BST	Initial fraction of soil water storage		0.25
CONA	Soil evaporation parameter		3.3
POROS	Soil porosity		0.43
SIA	Coefficient		0.2
CN2 SCS	Curve number		25.0
CHS	Main channel slope		0.01
WLW	Watershed width/ length ratio		1.23
RD	Maximum rooting depth	in	36.0
UL	Plant available water storage	in	i=1 0.38 i=2 1.9 i=3-7 2.28

For temperature and radiation a new set of empirical data was used for each year. As the radiation values have only been measured since 1972, average values were used for the first 12 years of the simulation. The average values for an 18-year time period for which the hydrology model had been run are listed in Table 2.

Information about the annual course of the leaf area index was gained from the Institut für Pflanzenbau of the Friedrich-Wilhelm Universität in Bonn. For the years 1974 to 1977 the dates of plant seeding and harvesting were available since a survey in the Mussum area had been made by the Landwirtschaftskammer Borken during these years.

The first runs of the hydrology submodel showed that percolation, which is the most important parameter for the simulation of nitrate leaching, was by far underestimated while the estimates of the value for evapotranspiration were too high for the prevailing climatic conditions. Sensitivity tests were made, where the input parameter, which had not been measured (BST, CONA, CN2, UL), had been changed. This did not lead to a satisfactory correlation of the results to the observed values. A revision of the input files based on the experiences gained at IIASA (Holy et al. 1982) did not bring significant improvement. The CREAMS results of deep percolation for the prevailing conditions ranged from 120 - 180 mm per year while the empirical observations ranged at 300 mm on an average.

Finally a change in the program was made, which caused some problems since there were some discrepancies between the program and the users manual, so that some of the variables and equations were difficult to locate. However this method seemed to be required as the hydrology model has an important influence on the following chemical nutrient submodel, so that 'percolation', the initial value for the following leaching results, had to be calibrated properly.

The best results were achieved by changing the equation of Eo, the potential evaporation, which has major significance in the soil water balance model. For the area investigated in this study Eo was used as

$$POTET\ (I) = 0.86 \cdot D \cdot HO/\ (D+GMA)$$

instead of

$$POTET\ (I) = 1.28 \cdot D \cdot HO/\ (D+GMA)$$

used in the program. No further changes proved to be necessary.

Results of the Hydrology Submodel

With the described change in the program, the model produced good results. The annual course of the water percolation as well as the annual amount of percolated water is reflected properly. For a time period from Sept. 1975 to Dec. 1977 the model delivered a mean percolation of 385.805 mm/year or 1.057 mm/day for one cropping pattern, as was observed in the Mussum area for the same period. The model was run twice over an 18-year time period with summer crops from 1960 to 1974 in both versions, and two different cropping patterns, which will be described later in this paper, for the time period 1975 to 1977. Both versions did not differ significantly. One led to a percolation of 411.318 mm/year, the other one to a percolation of 360.292 mm/year with an average of 385.805 mm/year for both versions from 1975 to 1977.

Table 2. Monthly temperature and radiation. Average values from 1960 to 1977.

Month	Temperature in ^{o}F	Radiation in langley/day
Jan	36.86	48.96
Feb	41.00	118.71
Mar	44.78	151.91
Apr	43.34	351.10
May	53.60	368.30
June	59.00	409.86
July	62.42	383.35
Aug	61.34	340.12
Sept	55.22	205.65
Oct	52.16	129.93
Nov	43.34	77.15
Dec	40.28	43.71

The measured data for the same period showed a mean percolation of 423 mm/year or 1.158 mm/day, which means an underestimation by the model of 8.74%. The results of the whole 18-years of simulations led to an average percolation of 294.68 mm/year, while 300 mm/year are given as an average percolation for the experimental area. The results of the model as well as the observed data are presented in Figure 2. The surface runoff was negligible in this area, which was also reflected by the model.

RESULTS OF THE CHEMICAL NUTRIENT SUBMODEL

As already mentioned in the introduction, the chemical nutrient submodel has only been tested for nitrate leaching. No simulations of pesticides losses have been done.

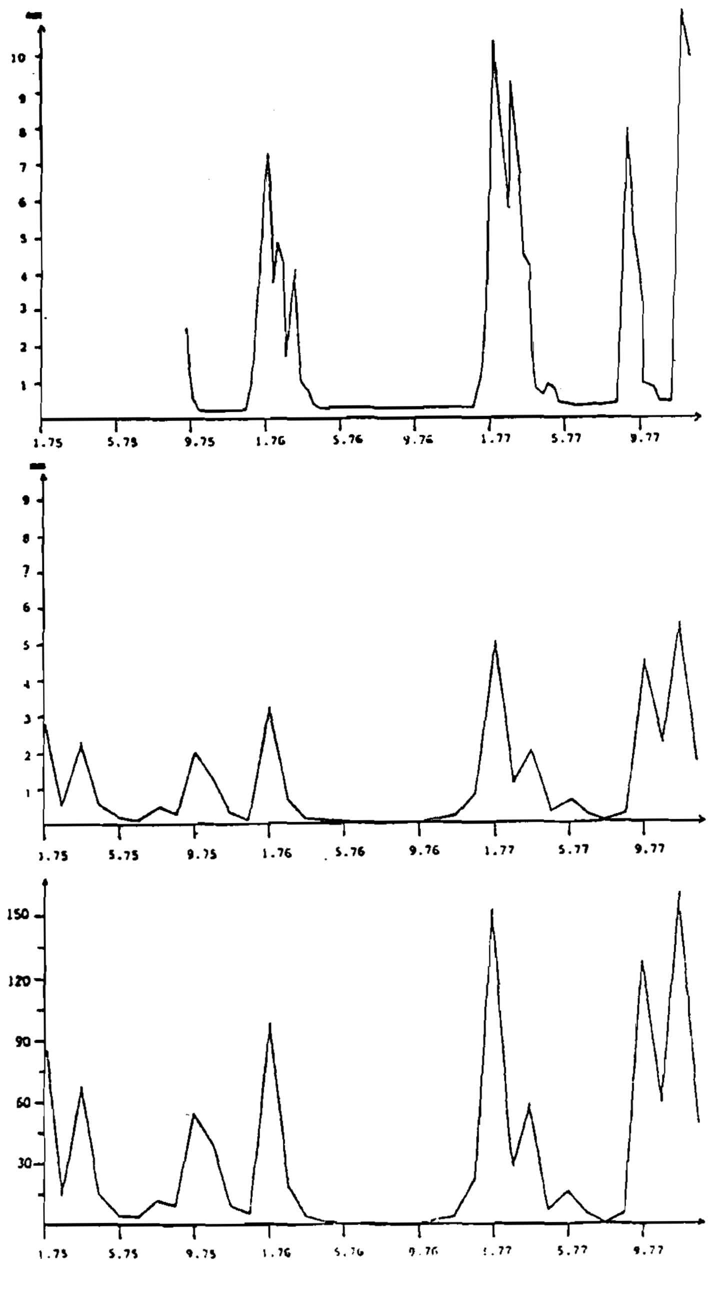
For the chemical nutrient submodel Option II was used. The information about the points of 50% and 84% N-uptake was gained from the Institut für Pflanzenbau of the Friedrich-Wilhelm-Universität in Bonn. There was quite detailed information available about fertilizing intensity, date of fertilizer application, potential N-uptake, time of plant emergency and harvesting, which had been gained by a survey of the Landwirtschaftskammer Borken.

In the Mussum area, as mentioned earlier, measurements of the nitrate concentration of groundwater had been made at several measuring stations.

In order to compare the results of the model with the empirical data of NO_3-leaching, the observations of two of the measuring stations where measurements were made close to the surface of the groundwater layer, were chosen. These observations seemed to reflect most properly the NO_3-concentration of the water percolated below the root zone caused by the agricultural practice and the cultivated crops. At measuring stations where the water had been taken

Figure 2. Observed process of percolation under arable land in the Mussum area in mm/day. Mean percolation 1.158 mm/d ≘ 423 mm/a

Simulation of the process of percolation for corresponding soil-, climatic- and agricultural conditions by CREAMS
Mean percolation 1.057 mm/d ≘ 386 mm/a gained from monthly averages



from deeper seams of the groundwater layer, the measured NO_3-concentrations did not quite reflect the nitrate leaching from the above cultivated crops as the deeper groundwater was mixed with water percolated from other fields. Due to the groundwater flow in the Mussum area this groundwater was mixed with water percolated mainly from less intensive grassland on the margins of the area, so that nitrate concentrations of the deeper groundwater layers were lower and more evenly distributed over time. The two cropping patterns simulated with the chemical nutrient submodel corresponded to the ones used in the hydrology submodel:

Cropping pattern I:	spinach (3 times)
	spring barley, rape, seeding of rye
	rye, fallowing, seeding of rye
	rye, seeding of winter barley
Cropping pattern II:	spinach (3 times)
	spinach (3 times), seeding of rye
	rye, spinach, seeding of rye
	rye, spinach

The fertilization was:

Cropping pattern I:

date:	74070	74166	74242	
amount in kg N/ha:	210	210	210	
date:	75062	75115	75260	
amount:	75	55	110	
date:	76066	76116	76136	
amount:	65	45	45	
date:	77069	77118		
amount:	65	41		

Cropping pattern II:

date:	74070	74166	74242	
amount:	200	200	200	
date:	75060	75150	75230	
amount:	180	180	180	
date:	76066	76116	76136	76204
amount:	75	40	40	160
date:	77069	77118	77218	
amount:	85	60	160	

A further calibration of this submodel has not been done although the calibration of the hydrology submodel led to a further underestimation of the NO_3-concentration per litre of percolated water because of the non-linear connection of the two submodels. The mean NO_3-concentration of the observations taken from the upper part of the groundwater layer was 209 mg NO_3/l for cropping pattern I with a maximum of 380 mg/l, and 214 mg NO_3/l for cropping pattern II with a maximum of 430 mg/l.

The results of the CREAMS model are 111.465 mg/l with a maximum of 312.72 mg/l for cropping pattern I, and 140.209 mg/l with a maximum of 451.192 mg/l for cropping pattern II. This difference in the mean concentration might possibly be caused by the zero leaching as estimated by the model, which did not occur in the empirical data. Nevertheless the results can be considered satisfying. The maximum values as well as the course of the nitrate-concentration are reflected well by the model. Figures 3 and 4 show the observed and simulation data of the NO_3-leaching process. Figure 5 shows the influence of different fertilizing methods on NO_3-leaching.

NO_3 LEACHING FUNCTIONS

The main intention in using the CREAMS model was to quantify the relationship between agricultural fertilization and nitrate concentration of the groundwater, especially for so-called 'problem areas' with light soils. Therefore the model was run for different fertilization levels. This was done for several products, which were run separately, not simulating a cropping pattern. As the estimates are not yet completely finished, only the results for two products will be given: silage-corn and winter barley.

The model was run for a 20-year time period (1960 to 1979) using the precipitation, temperature and radiation data set, as well as the input parameters reflecting soil conditions used for simulating the Mussum area (see Problems in Adjusting the Model and Tables 1 and 2). For the leaf area index as well as for the other parameters reflecting plant growth (YP, DMY, DOM, SD, PU) the average values for the prevailing climatic conditions were taken. For fertilizer application the customary dates were taken with two applications per year regarding the precipitation, temperature and radiation data available.

The NO_3-leaching was calculated for the following fertilization levels:

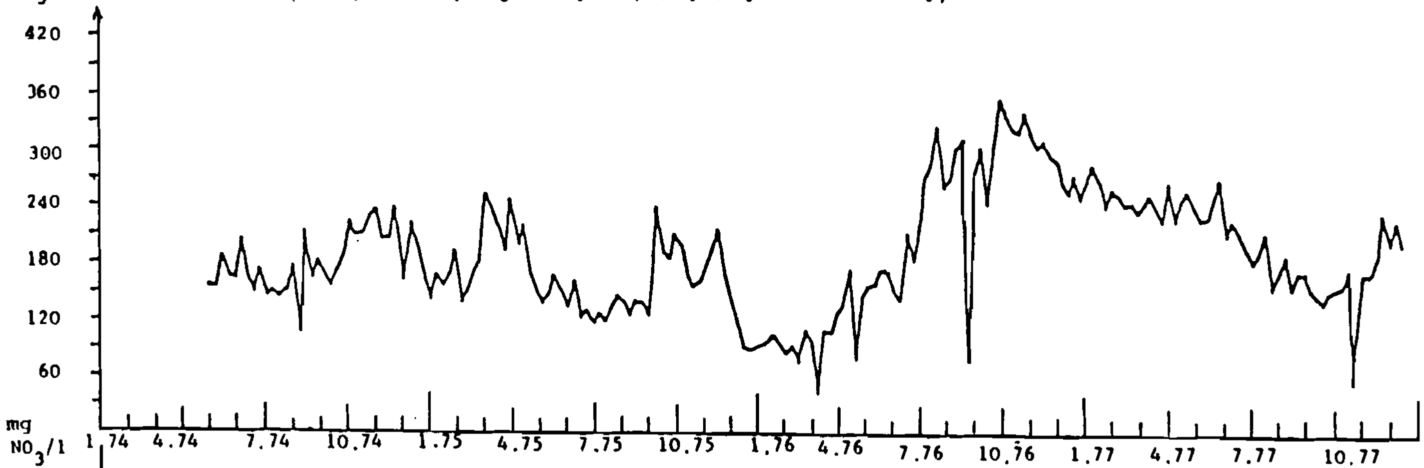
0, 40, 80, 120, 160, 200, 240, 280, 320, 400, 480 Kg N/lea.

The annual results differed considerably according to differences in the climatic conditions during the investigated years. With the 20 years' average results of NO_3-leaching in mg/l regressions were estimated using the method of least-squares estimators.

The best estimations were achieved by using a non-linear function of the type: $NO_3 = a + b.N + c.N^2$ where NO_3 = nitrate concentration in mg/l percolated water

N = fertilizer applied in kg N/ha.

Figure 3: Observed NO_3-leaching process in mg NO_3/l of cropping pattern I from 1974 to 1977 (3x spinach, spring barley, rape, rye, rye, winter barley) of the Mussum area.



Simulation of the NO_3-leaching process of cropping pattern I with the CREAMS-Model, monthly averages in mg NO_3/l from 1974 - 1977

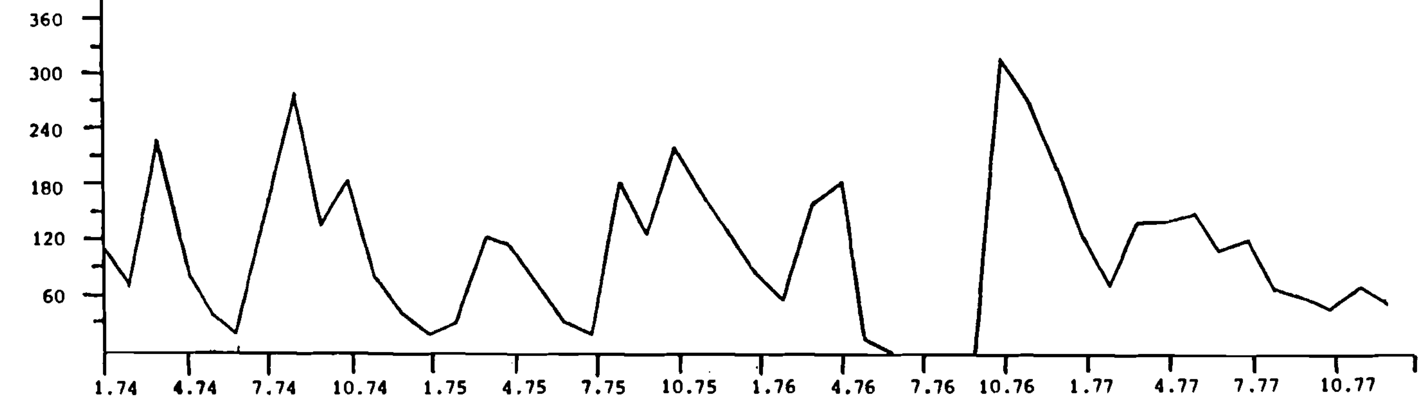
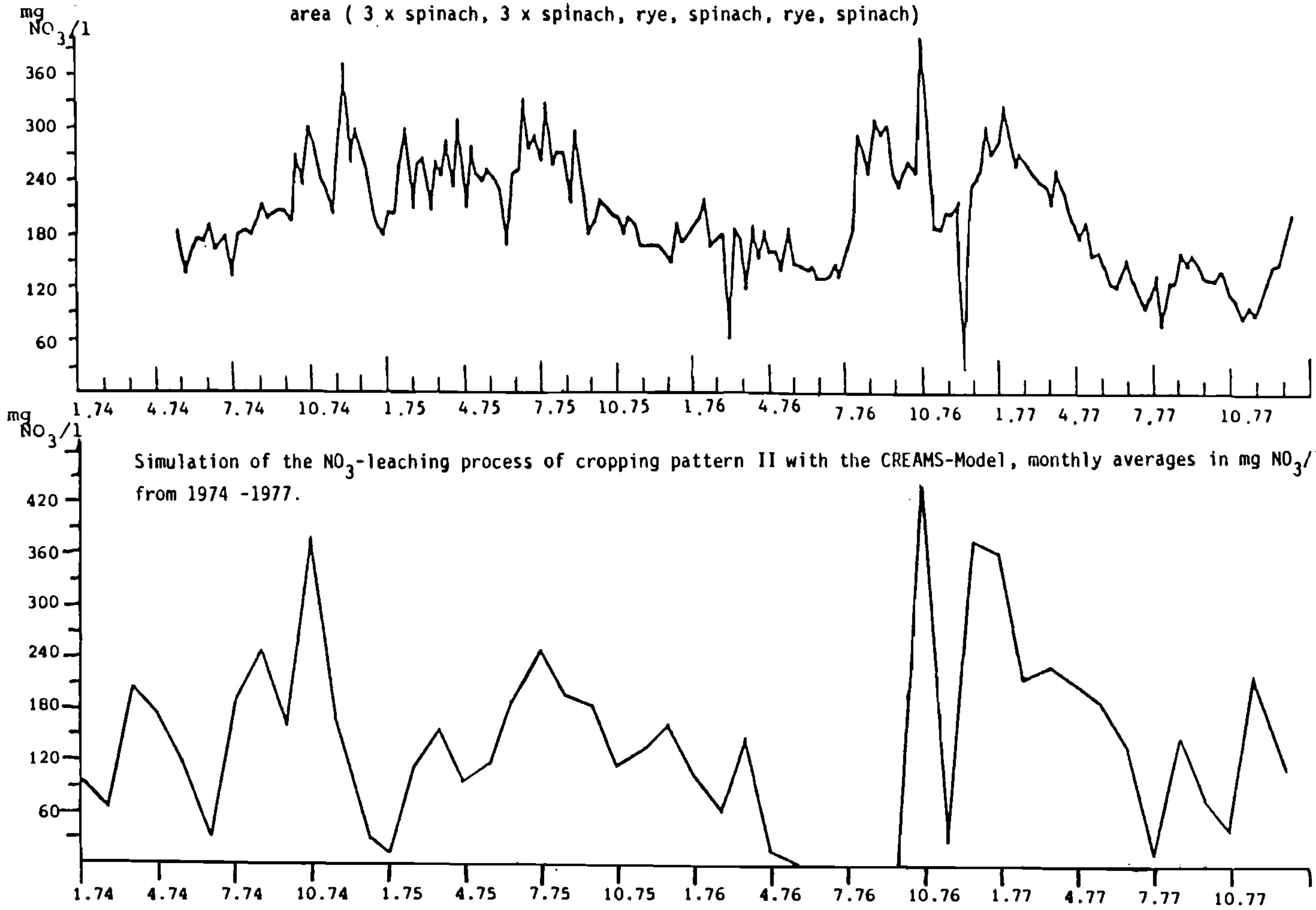


Figure 4: Observed process of NO_3-leaching in mg NO_3/l of cropping pattern II from 1974 to 1977 of the Mussum area (3 x spinach, 3 x spinach, rye, spinach, rye, spinach)



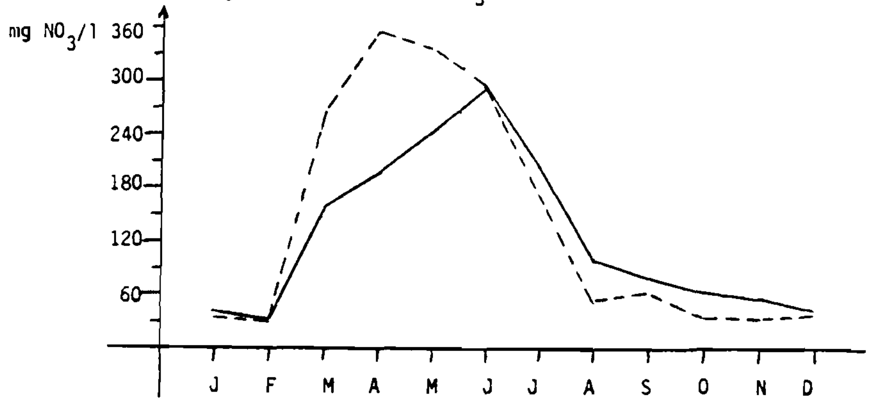
Simulation of the NO_3-leaching process of cropping pattern II with the CREAMS-Model, monthly averages in mg NO_3/l from 1974 -1977.

Figure 5: Simulations of NO_3-leaching to ground-water with the CREAMS-Model
Monthly averages of a 20 year simulation

CORN

---- Fertilizer application 215 kg N/ha (2 times : 161, 54)
average leaching: 136 mg NO_3/l percolated water

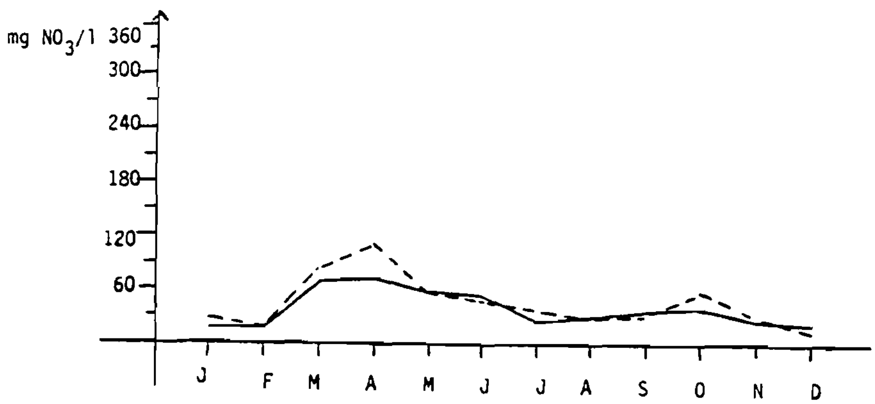
____ Fertilizer application 215 kg N/ha (3 times : 95, 70, 50)
average leaching: 110 mg NO_3/l percolated water



WINTER-BARLEY

------- Fertilizer application 80 kg/ha (2 times : 50, 30)
average leaching 42 mg NO_3/l percolated water

____ Fertilizer application 80 kg/ha (3 times : 40, 20, 20)
average leaching 36 mg NO_3/l percolated water



The estimated 'leaching-function' based on data generated by the CREAMS model are as follows:

Corn

$NO_3 = 8.39 + 0.3666\ N + 0.0010608\ N^2$

$R^2 = 0.991 \quad t = 4.159 \quad t = 3.334$

$DW = 1.191 \quad F = 382.4$

Degrees of freedom = 9

Winter barley

$NO_3 = 5.31 + 0.3072\ N + 0.00173\ N^2$

$R^2 = 0.995 \quad t = 3.31 \quad t = 6.075$

$DW = 0.998 \quad F = 655.1$

Degrees of freedom = 9

In order to prove these results and for further testing of the CREAMS model a number of publications were considered (Vömel 1970; Ceratzki 1973; Ohlendorf 1976; Braun 1978; Obermann and Bundermann 1978; Strebel and Renger 1978; Bundermann 1979; Sunkel 1979; Hay 1980; Obermann 1981), which also show a quantifiable relation between N-fertilization and NO_3-leaching. The data allowed neither a differentiation into several products nor a more detailed differentiation due to climatic conditions or management practices, but all observations stem from light sandy to moderately light silty soils with an annual percolation of 200 to 300 mm.

The 'leaching-function' estimated on this data base confirmed the type of non-linear function found by using the data base derived from the CREAMS model. The function is as follows:

$Nit = 23.59 + 0.3237\ N + 0.002202\ N^2$

$R^2 = 0.734 \quad t = 1.905 \quad t = 2.280$

$DW = 2.081 \quad F = 40.059$

Degrees of freedom = 29

All three functions show a quite similar progression. Especially the coefficients of the linear term show only little difference, while the coefficient of the quadratic term as well as the constant term is lower in the case of both functions estimated from CREAMS results. Some of the results gained from the estimated leaching functions are presented in Table 3.

The nitrate concentration leached from winter barley is higher than that from corn if higher fertilizer rates are applied, which seems plausible since the potential N-uptake of barley is lower than that of corn. That the leaching function estimated from observations shows higher leaching rates, can probably be explained by the fact that the data also includes products which show extremely high NO_3-leaching rates, as for example, vegetables.

Table 3. NO_3-leaching in mg NO_3/l derived from the estimated leaching functions.

Fertilizer Application in kg N/ha	NO_3-leaching in mg/l Data from publications	Data from CREAMS Corn	Winter barley
50	45.28	29.37	24.99
100	77.98	55.66	53.33
150	121.69	87.25	90.315
200	176.41	124.14	135.95
250	242.14	166.34	190.24
300	318.88	213.84	253.17
400	505.39	324.76	404.99
500	735.94	456.89	591.41

Besides, there are sometimes more than one observation for each year, so that years showing high NO_3-leaching concentrations might be over-represented.

Altogether the results of the estimations achieved on the data base gained from the CREAMS model well reflect the relationship between N-fertilization and NO_3-leaching according to present knowledge.

CONCLUSIONS

In conclusion it can be said that the estimations achieved with the help of the CREAMS model are satisfactory, since they produce a plausible simulation of NO_3-leaching for the area conditions described here as corroborated by the available empirical data to date.

Also, the process of percolation and leaching over time is well described by the model, after some adjustments were done. Until now the model has not been tested for any other soil type than the one described here. First sensitivity tests show, however, that both submodels are sensitive to changes of the input parameters characterising soil type and hydrological conditions (RC, FUL, BST, CONA, POROS, SIA, CN2 SCS, CHS and UL). With the leaching functions estimated from CREAMS results it is possible to quantify the relation between fertilization intensity of arable land and nitrate concentration in the water percolated below the root zone. This gives the initial information which is necessary to estimate cost-functions per hectare due to nitrate fertilization as the observed leaching can be valued with the costs of nitrate removal from groundwater.

However, these leaching functions describe the nitrate concentration of groundwater only for relatively thin and uniformly distributed groundwater layers. The groundwater flow, and therefore the problem of how the nitrate concentration of groundwater changes over time and over distance for various types of aquifers, is not reflected by the CREAMS model. Yet the model is quite useful for identifying "problem-areas", which might not only be the sandy soil area as assumed to date. It also gives facts which could help to re-examine the current norm of fertilizer use for economic and ecological reasons.

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APPLICATION OF THE CREAMS MODEL FOR CALCULATION OF LEACHING OF NITRATE FROM LIGHT SOILS IN THE NOTEC RIVER VALLEY

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INTRODUCTION

The objective of the present work was to use the CREAMS model (Knisel, 1980) for estimating nonpoint pollution of water with nitrate-nitrogen related to agronomic management, as well as to get additional data for planning optimum rates of nitrogen fertilizers recommended by the fertilizing advisory service.

The CREAMS model was applied for one representative field to estimate changes in the content of nitrate in the soil profile, leaching from soil in consequence of drainage below the root zone, and nitrogen loss in surface runoff. There is a need to extend the results over a selected water catchment area or region. The extension of simulation of nitrogen losses will be made for fields with crop rotation typical for the region and applied on basic soil types.

Climatic and cultivation data used in the study are from Chrzastowo located in the central part of Poland in the Notec river valley. In this valley, extensive investigations are carried out to extend the water economy system over the area of an agricultural region and to improve the water management principles in agriculture. The present work constitutes an element of these investigations.

The Noteć river valley region is characterized by relatively low precipitation amounts. The long-term mean annual precipitation is 516.9 mm. Cultivated mineral soils of this region are characterized by high infiltration rates. Most arable fields of the region are drained, and cultivation has been practiced for many years at a high agricultural level.

Among arable mineral soils of the region the following types prevail:

- loamy sands on loams, silts and clays - 47.8%
- loose, deep, weakly loamy sands on loamy sands - 20.7%
- deep loams or loams on silts or clays - 17.9%
- loose, weakly loamy sands on loams, silts and clays - 9.6%.

Present considerations are limited to light soils only (loose sands with underlying loamy sands, in this paper denoted as unitary field I), with assumption of average properties of these soils (Table 1). The following crop rotation is often applied in the region under study: summer barley, maize for silage, winter rye, potatoes. The simulation was started in 1960 with summer barley and finished in 1979 with potatoes. Some agronomic data for these crops under conditions of the region are quoted in Table 2.

Such an approach to the problem should enable the determination of the status of nitrate in the soil and the leaching for the field with average characteristics as an example of fields with light soils in the region under consideration. For working purposes these averaged features were defined as a unitary field, since the calculation results for this unit can be referred to all fields with the same soil type or at least to the fields with approximate soil profiles. Forecasts of the nitrogen leaching from cultivated soil of the region could then be based approximately on the sum of data for unitary fields with corresponding soil types prevailing there, multiplied by their respective area. Output data on the status of nitrate in the soil type under study and related to the post-vegetation period, can be of use for planning of the nitrogen fertilization for the next crop in the rotation.

The CREAMS model was applied with input data of unitary field I using precipitation data at Chrzastowo for the period 1960-1979.

RESULTS

The annual precipitation at Chrzastowo fluctuated considerably in the last two decades--from 307 to 729 mm (Table 3). Six dry years occurred with precipitation below 450 mm and also six wet years occurred when the precipitation amount exceeded 600 mm. The highest precipitation occurred in July and June; the lowest occurred in the winter months (Table 4).

Torrential rainfalls are rare in the Chrzastowo region. There were 47 days with precipitation over 20 mm and only 5 with more than 40 mm during the 20-year period. The highest daily precipitation amount, 81.6 mm, occurred in July 1961. Only sporadic occurrence of torrential rainfall resulted in surface runoff from the light soils under study. It has been calculated that in the whole 20-year period the surface runoff occurred on only six days, and the total runoff in the period was 45 mm. The largest daily volume of surface runoff (22 mm) occurred on July 31, 1961 from the 81.6 mm of rainfall. The topography of the region is flat, and therefore, the insignificant runoff on the light soils results in no erosion problem. A total of 1.70 tons per hectare of soil loss was computed for the 20-year period. Even if the land slope had been 15% there would not have been much soil loss.

The water drainage below the root zone of the plants cultivated generally occurred in the autumn and winter months, and most of the nitrate leaching from soil also occurred then (Table 4). There were 93 months in which the drainage occurred during the whole 20-year period. The drainage occurred quite rarely in the summer months, but in case of its occurrence in May, June or July, large amounts of nitrate were leached since fertilizer was applied in the spring. The leaching was proportional to the amount of mineral nitrogen fertilizers not utilized by plants. The calculated linear correlation coefficient between the drainage volume in a month and the amount of nitrate leached at that time was 0.574 and was significant at $p = 0.001$.

Table 1. Soil parameters

Effective saturated conductivity of the soil	0.34 in/hr
Fraction of pore space filled at field capacity	0.63
Soil evaporation parameter	3.4
Soil porosity	0.39 cm^3/cm^3
Immobile soil water content at 15 bars tension	0.08 cm^3/cm^3
Initial abstraction coefficient for SCS Curve Number method	0.2
Two conditions SCS Curve Number	78 for potatoes 69 for barley 72 for maize 67 for rye
Channel slope	3%
Bulk density	1.61 g/cm^3
Organic matter content	1.10% of soil mass
Field capacity	0.25 cm^3/cm^3
The content of particles with diameter 0.02 mm	12.0% of soil mass
The content of particles with diameter <0.002 m	4.8% of soil mass

Table 2. Nutrient parameters

	Barley	Maize	Rye	Potatoes
Maximum depth of the root zone (mm)	635	601	580	559
Potential yield (kg/ha)	9200	20000	9000	40000
Dry matter yield ratio	2.5	2.5	2.5	4.0
Mid point in nitrogen uptake cycle - DOM (days)	55	45	67	62
Standard deviation of DOM (days)	12	21	18	30
Potential nitrogen uptake (kg/ha)	90	120	85	160
Total nitrogen applied (kg/ha/year)	90	140	100	90
Number of nitrogen applications	2	2	2	1
Date of plant emergence	25 III	25 V	15 III	15 V
Date of plant harvesting	10 VIII	20 IX	2 VIII	15 IX

Table 3. Output data: annual totals

Year	Precipitation mm	Drainage mm	Number of months when drainage occurred	Nitrate leached kg N/ha	Denitrification kg N/ha	Calculated concentration of nitrate in drainage mg N/dm^3	Uptake of Nitrogen by plants kg N/ha
1960	536.2	81.5	5	10.8	23.3	1.33	71.1
1961	696.0	131.3	9	23.3	44.8	1.77	121.9
1962	540.8	71.4	3	5.9	12.3	0.83	85.0
1963	518.7	137.7	6	37.7	71.5	2.74	48.4
1964	408.7	53.3	4	12.9	34.8	2.31	43.3
1965	559.4	102.6	5	17.0	33.2	1.66	72.0
1966	559.8	130.3	6	53.6	75.3	4.11	48.1
1967	718.5	162.8	6	23.6	55.3	1.45	43.2
1968	501.4	99.8	4	15.3	31.4	1.54	44.9
1969	307.4	16.5	2	2.3	8.4	1.41	39.7
1970	680.9	168.1	7	69.5	109.8	4.13	77.7
1971	374.4	7.1	1	0.7	1.5	0.98	54.4
1972	449.6	0	0	0	0	-	95.0
1973	638.8	177.5	6	75.3	93.4	4.24	107.4
1974	729.1	283.2	7	29.7	50.4	1.05	55.3
1975	363.8	23.4	3	8.3	12.9	3.57	48.3
1976	459.2	109.5	4	33.4	89.3	3.05	34.1
1977	697.6	175.8	6	33.7	39.7	1.92	97.4
1978	549.9	144.5	5	33.0	69.5	2.28	42.0
1979	426.6	71.9	4	13.0	30.6	1.81	53.9

However, the value of this coefficient proves that the drainage volume would not be a good index of nitrate leaching. The soil temperatures of January and February are in that region usually below 0°C, and in these months no drainage and leaching of nitrate should be expected. The drainage and losses of nitrate calculated for January-February should not be considered accurate occurrences. During the period of investigation, the drainage in these two months averaged about 30% of the annual drainage, and mean leaching of nitrate was about 25% of the annual leaching. Most nitrate leaching occurred when dry years were followed by years with heavy precipitation, as in 1970 and 1973, but this relationship was not true for 1977. In dry years, little denitrification occurs, and uptake by crop is not as great as in wet years. This results in higher soil nitrate levels when heavy rainfall occurs in the following year.

Table 4. Output data: monthly mean values

Month	Precipitation mm	Drainage mm	Number of months when drainage occurred	Nitrate leached kg N/ha	Denitrification mg N/ha	Calculated concentration of nitrate in drainage mg N/dm^3
I	30.2	22.4	18	3.69	6.32	1.68
II	23.3	10.8	14	2.15	3.70	1.71
III	30.0	6.9	7	1.17	1.22	1.52
IV	36.1	3.1	5	1.33	1.54	2.89
V	57.3	6.5	6	2.60	2.87	3.84
VI	57.3	3.5	5	1.88	3.60	5.48
VII	80.7	3.7	3	1.62	2.40	4.58
VIII	50.5	0.15	1	0.05	0.64	3.08
IX	47.5	0.7	2	0.42	1.85	6.41
X	47.1	7.8	4	1.78	3.30	4.10
XI	48.4	16.2	11	3.99	8.34	2.72
XII	35.8	25.7	17	4.25	8.60	2.25

Output data concerning drainage and leaching of nitrate in subsequent months were used for the calculation of presumed concentration of nitrate in the percolation. The calculated average concentration was always lower than 10 mg N/dm^3 and lay generally between 0.15 - 7.55 mg N/dm^3 (Tables 3-4). There was no defineable relationship between the annual precipitation and calculated discharge-weighted nitrate concentration in the percolation (Table 3). However, the concentration was always higher in the spring and summer months than in the autumn and winter.

Denitrification occurs when soil water content is greater than field capacity. Similar to the leaching of nitrate, denitrification occurred in the autumn and winter months (Table 4). The nitrogen losses due to denitrification were low in dry years, but the annual losses were not always directly related to the annual precipitation amount (Table 3). The calculated linear correlation coefficient between the percolation volume in a month and the nitrogen losses due to denitrification was 0.400. This coefficient is significant at $p = 0.01$, but the linear relationship is not good. Nitrogen losses from soil due to denitrification were always higher than losses due to leaching of nitrate. The calculated linear correlation coefficient between the amount of leached nitrate in a month and the nitrogen losses due to denitrification was 0.815 and was significant at $p = 0.001$. The high degree of correlation exists because both processes occur when soil water content exceeds field capacity.

Considerable amounts of nitrate remained in the soil after the growing season in the years with low or average precipitations which do not lead to an excessive moisture content in the soil (Table 5). These often high reserves of nitrate cannot in all cases be utilized by the following crop, as in the autumn-winter season when the leaching and denitrification processes lead to considerable losses of nitrate. Nonetheless, there are years in which over 30 kg of nitrate-nitrogen per hectare remain for the subsequent crops.

DISCUSSION

The calculated leaching of nitrate below the plant root zone, averaged about 25 kg N per hectare a year. This constitutes a threat to the purity of water and is of importance for economizing fertilizer. However, some shortcomings in the estimation in view of different conditions between the USA and central Europe cannot be excluded. It seems that the yields calculated on the basis of the nitrogen uptake by plants is lower than observed yields, and this would result in differences in the overall nitrogen balance. Another problem results from the fact that the soil surface in the region is usually frozen in January and February. This is not considered in the model. The soil freezing limits the water percolation and the denitrification process. A part of snowmelt infiltrates into the soil, and more percolation and leaching of nitrate occur in March than is calculated by the model.

The ranges of the calculated average concentration of nitrate in drainage water were confirmed by the results of measurements of this concentration in water from the drainage network of the region under study. Also, the ranges of the calculated concentration of nitrate in soil after the growing season corresponded with those encountered in soils of the region. These similarities in the ranges of calculated and observed concentration of nitrate in soil suggest that the output data of the model can be useful for forecasting the water pollution and the nitrogen balance in soil. It seems also that the methodically and technically simplest way of verification of the reliability of output data of the model would be the measurement of the content of nitrates in soil after and before the growing season.

The simulations as described above were carried out on too small a scale for their reference to larger areas of arable soils. Supplemental data should consider different fertilization rates and dates, and cultivation dates as well as different physical properties of the soil type considered would be necessary. This would require carrving out additional simulations. Only the average values for different output data can be used for extending forecasts of the processes of interest over wider areas.

SUMMARY

The CREAMS model was used for calculation of the amount of leached nitrate below the plant root zone and of the nitrogen balance in light soil with average physical properties occurring in the Notec river valley. The input data were climatic and cultivation conditions in the locality of Chrzastowo situated in central Poland, i.e., the Notec river valley. The simulation was performed with the precipitation data for the period 1960-1979. The calculated nitrate leaching averaged about 25 kg N per hectare per year, which constitutes a threat for the water quality and fertilizer economy. Higher nitrogen

Table 5. The content of nitrate in the root zone (kg N/ha)

Year	At the end of October	At the end of February	The content of nitrate at the end of February in percent of this content at the end of October previous year	Crops
1960	41.0	-	-	barley
1961	9.8	15.0	36.6	maize
1962	37.4	4.7	48.0	rye
1963	66.3	24.2	64.7	potatoes
1964	67.8	9.3	14.0	barley
1965	88.3	25.4	37.5	maize
1966	89.5	37.7	42.7	rye
1967	2.6	12.7	14.2	potatoes
1968	66.6	2.5	96.2	barley
1969	119.9	16.8	25.2	maize
1970	54.6	70.9	59.1	rye
1971	78.2	14.2	26.0	potatoes
1972	97.3	81.1	103.7	barley
1973	32.5	75.9	78.0	maize
1974	8.5	5.5	16.9	rye
1975	65.7	4.5	52.9	potatoes
1976	95.8	29.7	45.2	barley
1977	33.6	11.8	12.3	maize
1978	27.4	17.6	52.4	rye
1979	-	7.0	25.5	potatoes

losses from soil were due to the denitrification process. The largest amounts of nitrate leached and percolation occurred in the autumn-winter months. It seems that the most feasible method of verification of the reliability of model output would be the measurement of the content of nitrate in soil after and before the growing season.

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APPLICATION OF THE CREAMS MODEL: WESTERN SKÅNE, SWEDEN

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INTRODUCTION

Water management problems of Sweden are primarily problems of water quality (Andersson et al., 1979). The major types of pollution Swedish authorities have to contend with include waste water discharge from point sources into water bodies, leaching of point source waste disposal into groundwater, and nonpoint source pollution of surface and groundwater by acidification and nutrient leaching. During the 1960s and early 1970s, environmental concerns were directed primarily towards the point source pollution of surface waters. The Environmental Protection Act of 1969 was especially important in combating the waste water discharge pollution (Andersson et al., 1979). Also, the risk for pollution from accidental spills has been reduced considerably by the adoption of very strict rules concerning the handling of hazardous materials (Miljödatanämnden, 1981).

The environmental concerns exhibited during the last 5 to 10 years have gradually changed from the easily detectable pollution sources affecting surface water to the often more severe, diffuse sources affecting surface and groundwater. Today, acidification of lakes, streams, and groundwater is regarded as a serious threat to the environment. The problem is well documented and intensively discussed at the ministerial level such as at the Stockholm Conference in 1982 (Swedish Ministry of Agriculture, 1982). The second nonpoint source pollution problem, presently being brought to general attention, is the nutrient leaching, primarily from agricultural lands (SNV, 1979).

The nutrient leaching problem is, in general, one of land use, and the effects related to the soil and water interactions. Both of these aspects are considered in the CREAMS field-scale model for evaluating nonpoint source pollution. This paper describes a first attempt to apply the CREAMS model to Swedish conditions in evaluating the effects of different agricultural management practices.

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NUTRIENT LEACHING PROBLEMS

The problem of nutrient leaching is a primary concern today in the Swedish environmental discussions. Although full understanding of the problems of eutrophication of the lakes in Southern Sweden has not yet been reached, it seems reasonable to believe that nutrient leaching is a main cause. Eutrophication is observed especially in areas with extensive agriculture, as for example, in Skåne. The two major lakes in Western Skåne, Vombsjön, and Ringsjön, are extremely eutrophic, with heavy algal growth each summer. This causes severe operating problems for the two water works which withdraw water from the lakes to supply the metropolitan areas along the coast (Figure 1). Also, the lakes are of great importance for outdoor recreation in the region as alternatives to the over-populated coastal shores. The attractive features of the lakes are considerably reduced however, by the algal growth, which causes problems to swimmers, fishermen, and weekend-house users.

The lakes are not the only water bodies affected by eutrophication. In recent years, the algal growth problem has been observed in the near-shore coastal areas. Again, it is argued that nutrient leachate is transported by the rivers to the sea. The main source probably is the agricultural fields in the watersheds.

Perhaps an even more serious problem is the recently observed high concentrations of nitrate in drinking water from groundwater wells. These observations are mainly in private wells in agricultural regions such as in Skåne where concentrations as high as 1,000 mg NO_3/l have been reported. The Swedish standards for nitrate in drinking water are essentially those of the WHO: water with concentrations exceeding 50 mg/l of NO_3 should not be given to infants and water with concentrations exceeding 100 mg/l of nitrate should not be used at all for drinking purposes.

Although the reason for high concentrations in private wells often is the direct inflow of drainage water into wells dug, the nitrate problem is more general.

Water quality statistics published by the Swedish Water and Sewage Works Association on municipal water sources show increasing nitrate concentrations in several regions, all of which are characterized as agricultural. Among these are the counties of Kristianstad and Malmöhus in Skåne. In general, the municipal systems have not reached the tolerance limits for nitrate concentrations, but the trend is obvious.

Two cases in the Skåne region where municipal groundwater wells have been abandoned should be mentioned. The first concerns the water supply source of Veberod, a small village in the Kävlinge River Basin. Due to high concentrations of nitrate in the groundwater, the local supply system was connected to the regional Vomb system in 1977 (Hjorth et al., 1979). On a larger scale, the municipality of Höganäs in Northwest Skåne had to stop groundwater use for almost half of the municipality in 1980 and connect that part to the regional Ringsjö system because nitrate concentrations averaged about 60 mg NO_3/l (Bjelm et al., 1980).

There seems to be no direct and easy method today to solve the nitrate problem. In a short-term perspective, there are essentially three alternatives:

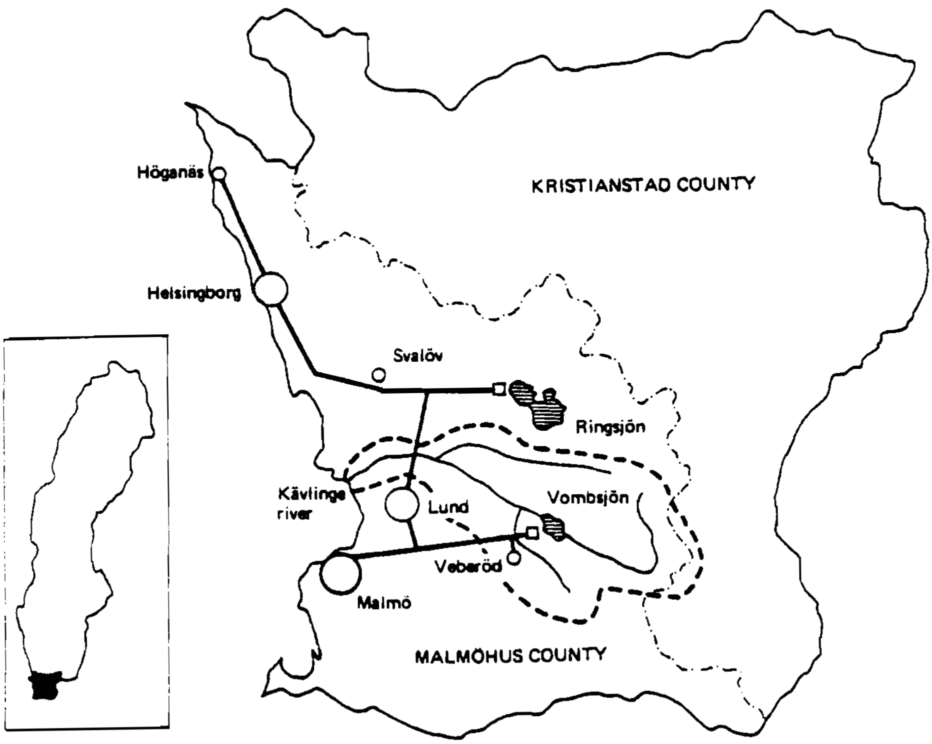

Figure 1. Skåne, Sweden

i) water treatment with an ion exchange system;

ii) mixing with less polluted water;

iii) move to new water supply sources.

The first alternative is expensive and difficult to operate. The other two alternatives are also expensive and may not be long-term solutions if the trend continues with increasing nitrate concentrations. Therefore, the interests for long-term measures is obvious, and changes in agricultural management practices, if they are the cause, are necessary and are to be recommended.

CREAMS MODEL APPLICATION

In view of the nitrate problems in groundwater and the difficulties of overcoming the problems with short-term measures, there is considerable interest in examining long-term measures. If management of agricultural land is the principle source of nitrate leaching, as is believed, then changing agricultural management practices must be considered. Interest is rapidly developing within the Swedish Ministry of Agriculture through the National Environmental Protection Board and its research program "Environmental Consequences of Management Practices in Agriculture and Forestry--Leaching of Crop Nutrients" which began in 1979. This program contains, among others, studies of nitrogen leaching from different soils under different cropping systems based on test observations.

In a joint study between the IIASA Tasks, Environmental Problems of Agriculture and Regional Water Management, it was decided to test the CREAMS model on conditions representative of Skåne and especially the Kävlinge River Basin which was central to the Resources and Environment Area's case study of Western Skåne, Sweden.

A large part of the Kävlinge River Basin has sandy soils suitable for growing potatoes, a situation which is regarded as potentially most severe with respect to nitrate leaching. The IIASA study is timely and an interesting complement from the perspective of Swedish research on nutrient leaching.

Agricultural statistics for the region show that wheat is, by far, the most common crop. It was decided, therefore, to compare a situation of wheat on clay soil with that of potatoes on a sandy soil. In accordance with the structure of the Skåne case study emphasizing the problems of irrigation, it was decided also to evaluate the leaching characteristics of non-irrigation and irrigation for each of the two crops. Thus, two different management practices on two soil types were tested, all with normal fertilizer application:

i) potatoes on sandy soil with rainfall only;

ii) potatoes on sandy soil with supplementary irrigation;

iii) wheat on clay soil with rainfall only;

iv) wheat on clay soil with supplementary irrigation.

Although the CREAMS model was developed to evaluate different management practices on a field level, it is used here for a regional management problem to evaluate the differences in nitrate leaching between management alternatives common in the Skåne region. Therefore, watershed, soil, and cropping information are generalized, but they are relevant for Skåne conditions.

The climatic input for the CREAMS model consists of recorded, i.e., as representative as possible, for the Kävlinge River Basin. Daily precipitation from Vomb, monthly mean temperatures from Lund, and monthly mean radiation from Svalöv (Figure 1) were used in the case study. Figure 2 shows the monthly totals of precipitation and irrigation for the two-year simulation period, 1976-1977, and the mean monthly temperature and radiation for the period. The nitrogen content of rainfall, 2 ppm, corresponds well with measurements made along the west coast of Sweden.

A 10 ha. area was considered to be representative of a field in the Kävlinge River Basin. Since the model application is made for the generalized situation, a uniform slope was assumed with an average of 0.03 m/m.

Soil data were taken from soil characteristics published by the Swedish University of Agricultural Sciences (Andersson and Wiklert, 1972). The textural composition for sandy soils and clay soils representative for Skåne is shown in Table 1. On the basis of soil composition, such parameters as soil porosity and saturated hydraulic conductivity were calculated. Field capacity and plant-available water capacity for each soil type are also shown in Table 1.

Crop data and farming operation information were obtained in discussions with representatives of the University of Agricultural Sciences. The information includes planting and harvesting dates, optimum yields for potatoes and wheat, fertilizer application dates and rates, and tillage dates. Selected information is given in Figure 3. Potatoes are planted about May 1 and 140 kg N/ha is applied on that date. Harvesting is done about September 20 with plowing under the potato vines about October 1. Incorporation of the crop residue is assumed to return about 20 kg/ha of potentially mineralizable nitrogen, with an addition of 20 kg N/ha in manure on November 1. Spring wheat is grown in Western Skåne. Wheat is planted about April 20 and about 70 kg N/ha is applied at planting time. Wheat is harvested about August 10 and the straw is plowed into the soil on October 1. The crop residue (straw and roots) is estimated to contain 20 kg/ha of potentially mineralizable nitrogen. The CREAMS model was applied for a continuous crop system, that is, potatoes on sandy soil, both years of simulation, and wheat on clay soils, both years of simulation.

Irrigation amounts and application dates were derived from a "rule-of-thumb" for supplementary irrigation commonly practiced in Sweden. The rule is based on information about crop water needs, suitable application rates for the soil type, and rainfall preceding application dates (Arthur, 1980).

DISCUSSION OF SIMULATION RESULTS

After the first simulation test of the hydrology component of the model, it was decided to omit the erosion component from the study. The reason is that climatic and soil conditions are such that only a negligible amount of surface runoff occurs. Moreover, since the study concerns nitrate leaching with percolation, the nutrient transport connected with negligible erosion

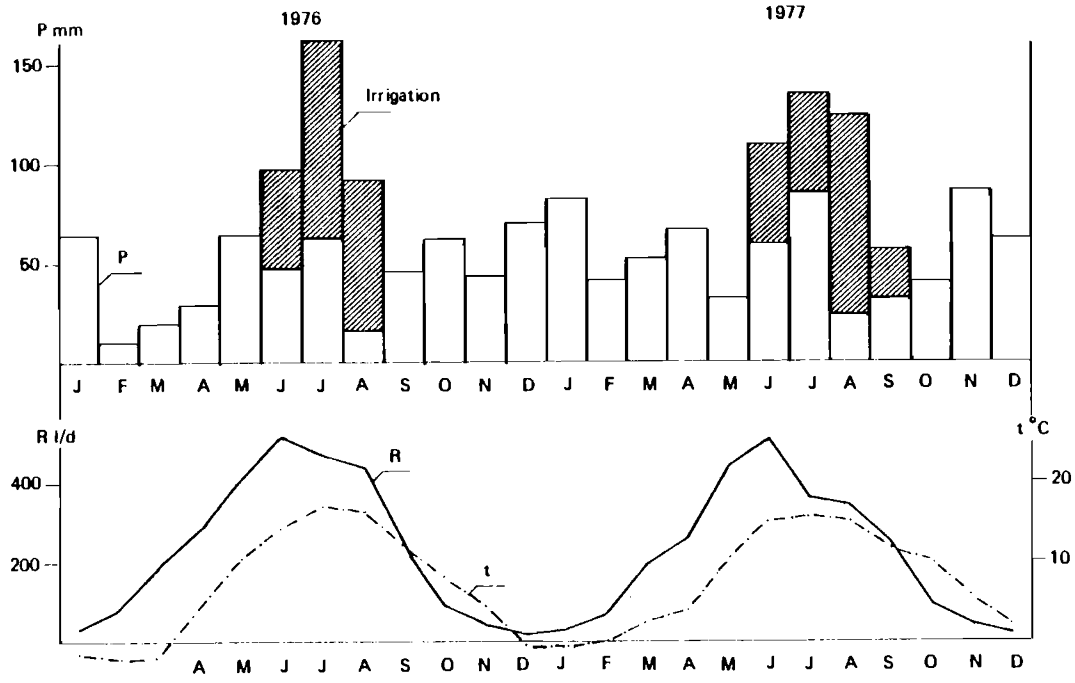

Figure 2. Precipitation, Irrigation, Radiation, and Temperature, Monthly values 1976-1977

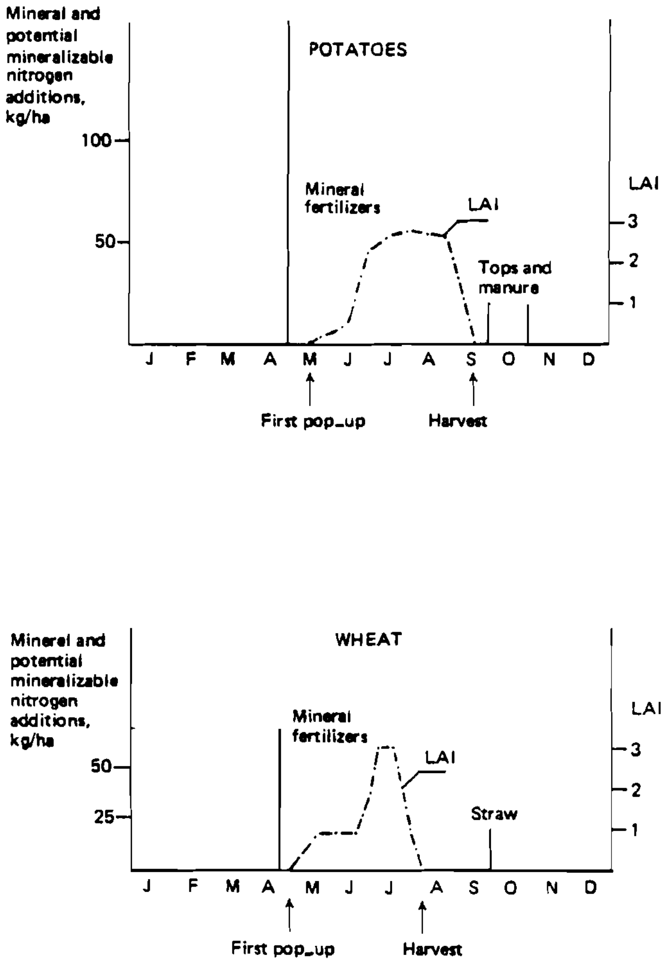

Figure 3. Crop data and farming operation, potatoes and wheat

Table 1. Soil composition and water-retention characteristics

Soil Type	Soil Composition			Water-retention Characteristics	
	Sand	Silt	Clay	Field Capacity	Plant-available Water
	(------Percent--------)			(------------Percent Volume-----------)	
Sand	82	15	3	18	10
Clay	38	32	30	36	14

and sediment yield is of minor interest. The pesticide component of the model is not relevant in the present study. Thus, the simulation study for the two-year period, 1976-1977, included only the application of the hydrology and nutrient components of the model.

The simulation results are summarized in Table 2, which shows yearly totals of the components of interest for each crop, management practice, and year. For potatoes on sandy soils, the 225 mm of supplementary irrigaton in 1976 resulted in 28 mm of percolation, more than occurred with rainfall alone. Increased percolation resulted in an increase of nitrate leached from 29 kg/ha to 36 kg/ha. In 1977, which had higher amounts of rainfall, the supplementary irrigation increased percolation by 106 mm and leaching of nitrate by 15 kg/ha. For wheat on clay soil, the tendency is the same for evapotranspiration and percolation. However, leaching does not increase with increased percolation. This is probably due to the low fertilizer application rates for wheat relative to the time of percolation increase.

Figure 4 shows the monthly distributions of percolation and leaching for three systems that were summarized by year in Table 2. In general, the nitrate leaching occurred during the early spring period when conditions for percolation are favorable and when high nitrate amounts are stored in the soil profile. Usually there is no leaching during the crop growing season because there is no excess rainfall or irrigation to cause percolation. However, when percolation occurs in early summer, the leaching rates may be very high due to the large amounts of recently applied fertilizer, especially for potatoes.

CONCLUSIONS

The CREAMS model hydrology and plant nutrient components were used in this study to evaluate the nitrate leaching from agricultural fields under different management practices. The model is a relatively simple simulation model based on readily available input parameters. The annual leaching amounts obtained correspond fairly well to results obtained from field experiments performed by the University of Agricultural Sciences (Andersson, 1982).

In evaluating nitrate leaching, some caution is necessary. CREAMS is not an absolute quantity predictive model. The relatively large summer

Table 2. Model simulation results, annual totals

Year	Crop/System	Precipitation + irrigation (mm)	Evapotrans-piration (mm)	Percolation (mm)	Nitrate Leached (kg/ha)
1976	Potatoes:				
	Rain	543	417	44	29
	+ Irrig.	768	660	72	36
	Wheat:				
	Rain	543	455	83	10
	+ Irrig.	768	640	111	11
1977	Potatoes:				
	Rain	667	525	142	21
	+ Irrig.	892	635	248	36
	Wheat:				
	Rain	667	500	172	11
	+ Irrig.	892	645	236	11

leaching shown in Figure 4 is dependent on small percolation volumes. Errors in estimating percolation may cause large errors in leaching output from the model. However, the principal purpose of the model is not to calculate absolute values, but to evaluate the differences between different management practices. In such evaluations, small input errors should not cause too much of a difficulty or problem.

In this case study, the simulation period was two years. This is too short a time with respect to errors in initial values of some input parameters, for example, initial soil water content or initial soil nitrogen content. The CREAMS document (Knisel, 1980) requires a minimum 3-year simulation period, but it recommends much longer periods. Probably for Swedish conditions, a 10- to 20-year period would be required to smooth out errors in initial values and also to account for different climatic conditions.

Results of the CREAMS application on Skåne conditions indicate the model is a promising tool to evaluate management practices for nonpoint source pollution control. Although the simulations were made for only two years, the results agreed relatively well with results from field experiments. Further application of the CREAMS model will help supplement field studies, and it will be possible to examine many potential management alternatives.

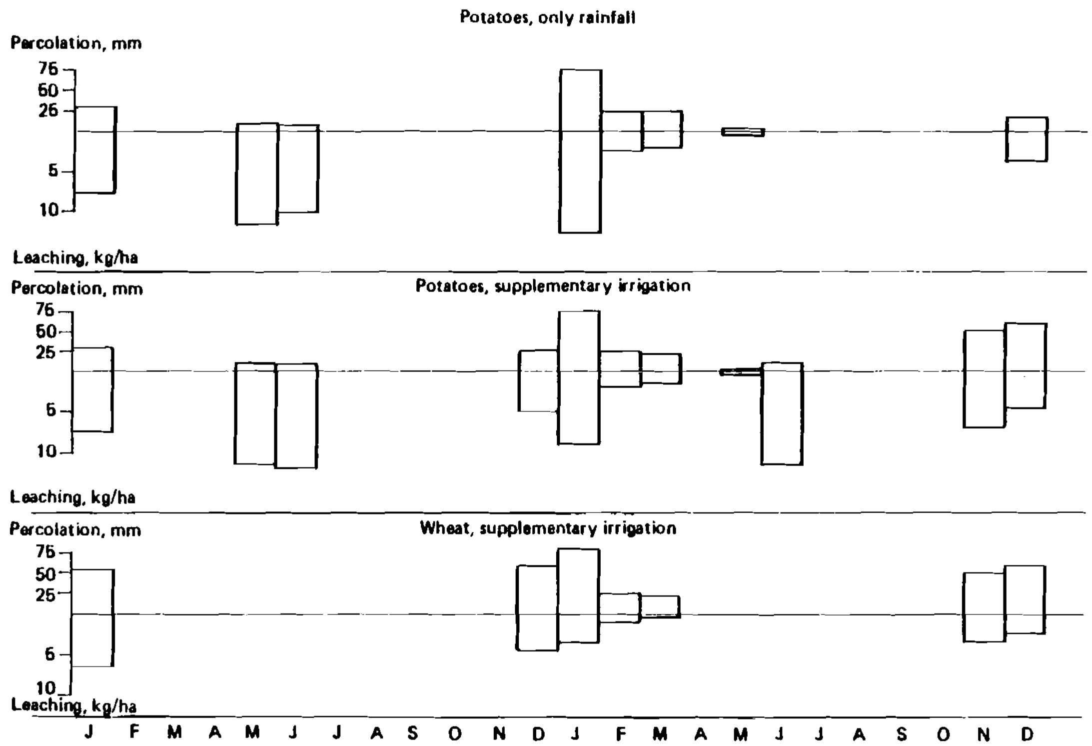

Figure 4. Monthly distribution of simulated percolation and leaching

For further application of the CREAMS model for Skåne conditions, other alternatives should be considered which are relevant to long-term measures against nonpoint source pollution. All tests should be based on at least 10-year simulation periods. The recommended alternatives are as follows:

- Continuing evaluation of supplementary irrigation versus non-irrigation. Initial studies indicate that appropriate irrigation applications may reduce nitrate leaching on a long-term basis due to higher amounts of crop nutrient uptake. Locally, however, irrigation may cause increases in leaching, especially when fertilizer application is made immediately before relatively heavy rainfall;
- Fertilizer application distributed over the growing season versus the normal one-time spring application;
- Reduced fertilizer application versus normal application rates which today are regarded as unnecessarily high;
- Application of manure in the spring which correspondingly reduces amounts of commercial fertilizer versus autumn application of manure;
- Application of protective autumn crops, such as hay following early potatoes, for example;
- Different crop rotations, especially those including hay.

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PREDICTING HILLSLOPE RUNOFF AND EROSION IN THE UNITED KINGDOM: PRELIMINARY TRIALS WITH THE CREAMS MODEL

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INTRODUCTION

The pollution of water resources by sediments, nutrients and pesticides and its effect on water quality is the concern of many organisations in the United Kingdom, including Regional Water Authorities; the Water Pollution Research Laboratory; the Ministry of Agriculture, Fisheries and Food; and the Institute of Hydrology (Department of the Environment, 1973a; 1973b). Although the techniques for monitoring and predicting point sources of pollution, e.g. factory discharges, are reasonably well-established, little attention has been given in the UK to the evaluation of non-point source pollution, e.g. the input of sediment and chemicals to rivers through surface and subsurface water movement on hillsides. This is in spite of recent public interest on the effects of nutrients and pesticides on water quality as a result of changes in agricultural and land management practices.

CREAMS is a field-scale model for assessing the chemicals, runoff and erosion arising from various agricultural management systems (Knisel, 1978; 1980). It comprises three sub-models or components: hydrology, erosion and chemicals. These predict, in turn, the volume of runoff, the rate of soil loss and the output of dissolved and absorbed chemicals. Working in conjunction with scientists from the International Institute for Applied Systems Analysis, Laxenburg, Austria, and supported by a research grant from the UK Natural Environment Research Council, the authors are studying the applicability of the CREAMS model to UK conditions, using data from a field study of soil erosion in the Silsoe area of mid-Bedfordshire.

Measurements of runoff and soil loss from plots were made in the Silsoe area between May 1973 and August 1979 as part of a study of soil erosion in the UK (Morgan, 1980a). Nine field plots were established on sandy, sandy loam, clay and chalk soils under bare ground, grass ley, cereals and woodland. Data are available for all plots for monthly, 100-day and annual periods and for one plot, sandy soil with bare ground, on a storm-by-storm basis. The experimental design and plot instrumentation are described in Morgan (1977).

The objectives of the application of the CREAMS model are:

1. to investigate the validity of the model under UK conditions;
2. to develop procedures for establishing values for the surface roughness and plant cover parameters used in the model, if possible replacing the currently employed empirical procedures with a more physically-based approach; and
3. to assess weaknesses in the model and develop strategies for improvement for UK conditions.

Since the Silsoe study did not include measurements of chemicals, only the hydrology and erosion components of the model were investigated.

The research programme started in January 1981 and it is not yet possible to comment on objectives 2. and 3. Preliminary validation trials have been completed, however, and this paper reports their results.

THE TEST DATA

The test data are taken from the plot monitored on a storm basis. The plot is situated on a convex-concave hillside with a maximum slope of 11°, on a bare sandy soil of the Cottenham Series, derived from the underlying sandstone strata of the Lower Greensand formation. Measurements of runoff and erosion were made at three slope positions on the plot: the upper convexity, the mid-slope and the lower concavity. Only data for the lower concavity are used in the test trials. The hydrology component is tested with daily data collected continuously between 1 May 1973 and 31 December 1974. During this period, 33 runoff events were recorded with amounts ranging from 0.02 to 16.59 l m^{-1}. The erosion component was tested with data from 33 storms occurring between 1 May 1973 and 30 June 1979. These included nine out of the ten most erosive storms in that period and six storms where no erosion took place. Storm soil loss values in the observed data set range from 0.0 to 26.3 t ha^{-1}.

THE HYDROLOGY SUBMODEL

Strategies

The hydrology sub-model is basically a water balance procedure operating on inputs of precipitation to give outputs of runoff volume, peak runoff, evapotranspiration, soil water storage and deep percolation. The estimates of runoff volume and peak runoff become inputs to the erosion sub-model. The estimates of runoff volume, deep percolation, and erosion become inputs to the chemistry sub-model. The hydrology sub-model can be used with either daily or breakpoint rainfall data. The daily option is tested here.

Runoff volume is predicted by the sub-model as an equivalent depth of water over the catchment area. This is then considered as the average depth over the catchment and total runoff volume is thus the product of depth and catchment area. Unfortunately, because the observed data were collected using sediment traps and unbounded plots for which the effective catchment area is not known, they cannot easily be expressed in depth form. It is possible to estimate a catchment area from the width of the traps (1 m) and an assessment from field observations of the average length of overland flow (50 m). This procedure could be used to define a catchment area for operating the sub-model.

It is doubtful, however, if the observed runoff volumes can be regarded as having been derived from this catchment area. Mean annual overland flow runoff varies from 57.9 l m^{-1} on the convexity, to 68.8 l m^{-1} on the mid-slope and 58.3 l m^{-1} on the concavity. Thus, there is very little variation in runoff between the traps at the upper convex and lower concave sites, a distance of 30 m. This implies that downslope additions of precipitation must be balanced by downslope losses through infiltration or, possibly, flow divergence. Since, with a uniform width of 1 m, slope length can be used as a surrogate for catchment area, these figures also imply that runoff volume is largely independent of area.

Clearly, defining the area from which runoff is generated is going to be somewhat arbitrary under these conditions. In previous work (Morgan, 1980a) on converting the measurements of soil loss per unit width to an area basis, an attempt was made to justify an effective slope length of 10 m based on the distance apart of depositional splays on the hillside after rain and on a comparative width-length scaling with standard USDA erosion plots. This approach is used here as one strategy and for this the observed volumes are converted to an average depth over 10 m^2. As an alternative, the runoff volumes were assumed to be derived from an area of 1 m^2, i.e., from a slope length of 1 m. Although this second strategy might appear somewhat extreme, it had already been used to give successful predictions of soil losses using the erosion sub-model (Morgan, 1980b).

Treating the observed data in this way means that they can be considered as representative samples of runoff depth for a given position on the hillside and it is not necessary to operate the sub-model for either of the contrived catchments of 1 m^2 or 10 m^2. Instead, to conform with the basis outlined above for the area assessment of soil loss, the sub-model is run for a 10 m^2 catchment. The results are compared with the 'observed' depths which are interpreted as indicators of average runoff depths within the catchment. Runoff predictions are analysed separately for the two 'observed data' strategies.

Input parameters

Two input files are required: a daily rainfall file and a hydrology parameters file. The daily rainfall file comprises daily rainfall amounts obtained from the meteorological recording station of the National Institute of Agricultural Engineering, 3 km from the field site.

The input to the hydrology-parameters file is listed in Table 1 and comments on selected parameters only are made here. Although the site has a sandy soil, knowledge of the local conditions indicated that if typical parameter values for sand were used, runoff would rarely be predicted. The infiltration capacity of the soil is over 200 mm h^{-1} and since the highest rainfall intensities recorded over ten minutes are only about 40 mm h^{-1}, theoretically no runoff should occur. Runoff generation is explained by the inability of dry sand to take in water because of surface tension and by crusting of the soil surface (Morgan, 1977). These effects must be simulated when determining parameter values.

Typical parameter values for sand were used for RC (2.0 in h^{-1}) and FUL (0.11), and, following the recommendations for operating the model (Foster et al. 1980, p. 339), a rooting depth of 36 in was assumed, giving a value of 16.2 in for UL. In order to reproduce the observed high rates of runoff, a high value of CN (92) was selected for the SCS Curve Number for the 10 m^2 strategy, indicating a soil of moderately high runoff potential.

Much higher runoff depths were required for the 1 m^2 strategy and to achieve these an attempt was made to simulate a sandy soil which behaved like a clay as regards runoff producing characteristics. A value of 0.6 in h^{-1} was

Table 1. Hydrology parameters file.

Parameter		Observed data strategy[a] 10 m^2	1 m^2
DACRE	Catchment area (ac); field data	0.002	0.002
RC	Effective saturated conductivity of the soil (in h^{-1})[b]	2.0	0.6
FUL	Fraction of pore space filled at field capacity[c]	0.11	0.77
BST	Fraction of plant-available water storage filled when simulation begins; assumed equal to FUL	0.11	0.77
CONA	Soil evaporation parameter[d]	3.3	3.3
POROS	Soil porosity in root zone[e]	0.50	0.50
BR15	Immobile soil water content at 15 bars tension (in in^{-1})[f]	0.05	0.05
SIA	Initial abstraction coefficient for SCS runoff equation[g]	0.2	0.2
CN2	SCS Curve Number for condition 2[h]	92.0	91.0
CHS	Channel slope (ft ft^{-1}); field data	0.156	0.156
WLW	Catchment length/width ratio; field data	50.0	50.0
RD	Rooting depth (in)[i]	36.0	8.3
UL	Plant available water storage (in)[j]	16.2	3.738
TEMP	Mean monthly temperatures (^{o}F)	Meteorological Office data from published records	
RADI	Mean monthly solar radiation (Ly day^{-1})	Meteorological Office data from published records	
GR	Winter cover factor; value for no cover	1.0	1.0
LAI	Leaf area index; no vegetation cover	Assume 0 for days 1-121; increasing from day 122 to maximum value of 0.02 on day 200; decreasing from then to 0 value on day 250; 0 for days 251-366[k]	

[a]For explanation, see text.

[b]Values based on Withers and Vipond (1974; Fig. 3.10, p. 75); explanation given in text.

[c]See Table 2 for derivation.

[d]Typical value for sand (Foster et al, 1980).

[e]Typical value for sand (Hall, 1945; p. 60).

[f]Typical value for sand (Withers and Vipond, 1974; Table 3.4, p. 71).

[g]Smith and Williams (1980).

[h]Values selected from Schwab et al. (1966; Table 4.1, p. 104).

[i]For explanation, see text.

[j]UL = (POROS - BR15) (RD) (D) where D = depth of storage layer. D = 1/36 RD for top storage layer, 5/36 RD for second storage layer and 1/6 RD for each of the remaining five storage layers (Foster et al., 1980).

[k]The sub-model does not operate with LAI = 0. A minimum value has therefore been used. Days refer to Julian dates.

used for RC. FUL was set at 0.77 but BR15 was kept at 0.05, a typical value for sand. Because of the absence of top soil at the field site and the difficulty of distinguishing between the soil and the weathered bedrock, a low storage capacity for the sand was simulated by reducing the rooting depth to 8.3 in, which resulted in a value of 3.74 in for UL.

Sensitivity analysis

A limited sensitivity analysis was performed, concentrating on those parameters appearing to have most influence on water storage and runoff. The analysis was carried out first on the simulation for predicting runoff at the field site using the 10 m^2 strategy and second on a typical data set for a clay soil without vegetation but with the same catchment area and slope characteristics as the field site. Although no observed data are available with which to compare the results of this second simulation, all the clay soil sites in the field study being used for cereals, the analysis was undertaken to determine whether the sensitivity of certain parameters was the same for different soils. The sensitivity analysis was restricted to changes in rooting depth (which influenced UL), the SCS Curve Number and FUL. Because changes in FUL imply changes in field capacity, they also imply changes in soil characteristics. To allow for these, the values of BR15 were also altered to those suggested by Withers and Vipond (1974) for a soil with the given value of field capacity. Values of FUL were then calculated as suggested by Foster et al. (1980, p. 338) from field capacity, porosity and BR15, using the values shown in Table 2. Two values were used for each of the parameters RD, CN and FUL, selecting values either side of a realistic range, rather than extreme values. They were combined in a factorial set, giving eight simulations.

Table 2. Derivation of values of FUL

Soil type	Field capacity (FC)	Porosity (POROS)	BR15	FUL
Sand	0.10	0.50	0.05	0.111
	0.15	0.50	0.08	0.167
Clay	0.40	0.55	0.25	0.50
	0.45	0.55	0.30	0.60

FUL = (FC - BR15)/(POROS - BR15) (Foster et al. 1980, p. 338); values for FC are taken from Withers and Vipond (1975; Table 3.4, p. 71).

This procedure allows the effects of possible interactions between the parameters to be estimated, a feature not possible in the sensitivity analysis of the hydrology sub-model carried out by Lane and Ferreira (1980).

Results of the hydrology simulation

Observed and predicted values of runoff are presented in Table 3. Three measures of the predictive success of the sub-model were employed. Because the uncertainty over catchment area throws doubt on the magnitudes of the 'observed' depths of runoff, it was felt that the first criterion of success should be to predict the occurrence of runoff on the right days. Secondly, ratios of predicted to observed values of runoff were calculated and the percentage of those within the range 0.75 to 1.5 was determined. Thirdly, product-moment correlation coefficients were calculated between the predicted and observed values.

The results for the 10 m^2 strategy show that 42 per cent of the runoff events were predicted on the correct day whereas for the 1 m^2 strategy 67 per cent are predicted. However, the simulation for the latter strategy predicts runoff on 23 days when it did not occur whereas that for the 10 m^2 strategy does this on only 4 days. The accuracy of the predictions is poor. With the 10 m^2 strategy ratios of predicted to observed values fall within the range cited above for only 15 per cent of the runoff events. For the 1 m^2 strategy, this figure is 12 per cent. Not surprisingly, correlation coefficients are generally low, though statistically significant. Taking all days on which runoff is either predicted or observed, $r = 0.285$ ($n = 37$; $p < 0.05$) for the 10 m^2 strategy and $r = 0.312$ ($n = 56$; $p < 0.01$) for the 1 m^2 strategy. The significance levels quoted in parentheses refer to one-tailed tests as only positive correlations indicate agreement between the model and observed

Table 3. Observed and predicted runoff values

Julian date	'Observed' data strategies 10 m2 Observed	Predicted	1 m2 Observed	Predicted
	(in)		(in)	
73170	0.038	0.387	0.38	0.45
177	0.043	-	0.43	-
178	0.035	0.047	0.35	0.23
187	0.028	0.312	0.28	0.66
196	0.025	0.016	0.25	0.09
219	0.008	-	0.08	-
239	0.034	0.027	0.34	0.12
258	0.001	-	0.01	-
263	-	0.016	-	0.11
270	-	-	-	0.03
272	0.008	-	0.08	-
308	0.026	-	0.26	-
354	-	-	-	0.04
74004	-	-	-	0.02
006	-	-	-	0.05
008	-	-	-	0.03
011	-	-	-	0.12
012	-	-	-	0.06
015	0.001	-	0.01	0.04
040	-	-	-	0.18
041	0.001	-	0.01	-
042	-	-	-	0.04
045	-	-	-	0.03
069	-	-	-	0.04
143	0.006	-	0.06	0.02
159	0.001	-	0.01	-
167	0.043	0.017	0.43	0.06
177	-	0.099	-	0.20
179	0.002	-	0.02	0.03
185	0.005	-	0.05	-
194	0.049	0.025	0.49	0.11
197	0.022	-	0.22	0.02
216	0.020	0.059	0.20	0.16
220	0.028	0.032	0.28	0.19
222	-	-	-	0.02
224	0.009	-	0.01	0.04
237	0.015	0.048	0.15	0.21
244	0.001	-	0.01	-
246	0.010	-	0.10	0.01
247	0.002	0.102	0.02	0.45
266	0.008	-	0.08	0.03
269	-	0.084	-	0.37
275	0.019	-	0.19	-
276	-	-	-	0.10
277	-	-	-	0.13
279	0.022	-	0.22	0.05
280	-	0.027	-	0.25

Table 3 continued

283	-	-	-	0.02
288	-	-	-	0.05
291	-	-	-	0.08
292	0.003	-	0.03	-
317	0.020	0.022	0.20	0.10
322	0.024	0.249	0.24	0.73
325	0.042	0.051	0.42	0.28
326	-	-	-	0.03
361	-	-	-	0.07

Regression equations (Y = predicted; X = observed)

$10\ m^2$ strategy: (1) all instances where either observed or predicted values are greater than zero

$Y = 1.66\ X + 0.0169$ $r = 0.285$ $n = 37$

(2) all instances where observed values are greater than zero

$Y = 2.07\ X + 0.0047$ $r = 0.332$ $n = 33$

(3) all instances where observed values are greater than zero but excluding events on 73170, 73187, 74247, 74325 (see text)

$Y = 0.68\ X - 0.0001$ $r = 0.543$ $n = 29$

$1\ m^2$ strategy: (1) all instances where either observed or predicted values are greater than zero

$Y = 1.44\ X + 0.1167$ $r = 0.312$ $n = 56$

(2) all instances where observed values are greater than zero

$Y = 0.33\ X + 0.0740$ $r = 0.339$ $n = 33$

data. Considering runoff events only, $r = 0.332$ for the $10\ m^2$ strategy and $r = 0.339$ for the $1\ m^2$ strategy ($n = 33$; $p < 0.05$ for both). However, an inspection of the ratios of predicted to observed values reveals that the simulation for the $10\ m^2$ strategy consistently overpredicts those events where low runoff volumes occur from high rainfall amounts of long duration and low intensity. Such overprediction is to be expected with the daily rainfall model which takes account of within-storm variations in rainfall intensity. If the four instances of these rainfall conditions are omitted, $r = 0.543$ ($n = 29$; $p < 0.01$).

The results of the sensitivity analysis are shown in Table 4. Clearly the predicted runoff was very sensitive to changes in the SCS Curve Number. Changes in RD had negligible effect for the sandy soil and a small effect for the clay soil. A relatively small change in FUL and its related parameters for the clay soil caused an increase in predicted runoff of about 40 per cent at CN = 88 and 25 per cent at CN = 92. Apart from this moderate interaction

Table 4. Total predicted runoff (in) for the study period for simulations used in the sensitivity analysis.

(1) Sandy soil			86		CN	88	
FUL	0.111		0.32			0.56	
	0.167		0.38			0.64	
Variation in RD from 30 to 36 in had negligible effect							
(2) Clay soil			30		RD	36	
		88	CN	92	88	CN	92
FUL	0.50	1.80		3.83	1.87		3.94
	0.60	2.48		4.82	2.60		4.98

between the effects of variation in FUL and CN, the parameter changes seemed to act virtually independently. These findings agree generally with the sensitivity analysis of Lane and Ferreira (1980), though they did not study RD directly but varied the values of UL which depend on both RD and FUL.

The sandy soil considered here differed from the clay soil and from the soil considered by Lane and Ferreira (1980) in that a relatively large increase in FUL caused only a 14-20 per cent increase in predicted runoff. This is perhaps to be expected as runoff on a sandy soil is more likely to be due to infiltration excess than to reaching saturation.

A small number of additional simulations were performed to investigate other less important sensitivity questions. It was found that changing CN to 90 and 92 for the sandy soil, with FUL = 0.11, caused a continued dramatic increase in predicted runoff to 0.96 in and 1.67 in respectively for the study period. Changing the value of BST, the fraction of plant-available water storage filled at the start of the simulation, had no effect on the results for the sandy soil, but some effect on the first year's predictions for the clay soil. For all the other simulations reported, the soil was assumed to be at field capacity when the simulation period began.

Discussion

Although the results obtained from the preliminary trials of the hydrology sub-model are poor, it is difficult to judge exactly how bad the predictions really are. The only previously published comparison of runoff predictions from the sub-model with observed values is for watershed P2, Watkinsville, Georgia, USA, a catchment of 1.3 ha (Lane and Ferreira, 1980). For 48 runoff producing events over the 1973-75 period, a correlation coefficient of 0.728 was obtained. However, by using only runoff producing events in assessing the success of the sub-model, no details are available of how frequently runoff was predicted when none occurred.

Because the sub-model is basically the SCS Curve Number model of runoff prediction with a water balance procedure added to it, the potential of the sub-model can be gauged by examining the reliability of the SCS Curve Number method. Smith and Williams (1980) present test results from this model for 37 catchments ranging from 0.25 to 12.95 ha. Correlation coefficients range from 0.03 to 0.95. Only 14 per cent are less than 0.5, however. Judged by these standards, only the simulation for the 10 m^2 strategy and ignoring long duration storms can be considered satisfactory.

Ideally the slope of a regression line for predicted values against observed values should equal 1.0. In the case of the Watkinsville P2 data, the slope was 0.72 and the sub-model overpredicted for low volumes of runoff and underpredicted for high volumes. For observed runoff events only, the slope values obtained in this study are 0.33 for the 1 m^2 strategy and 2.07 for the 10 m^2 strategy. If the four long-duration storms are omitted, the slope for the 10 m^2 strategy falls to 0.68. Again, this can be considered the only satisfactory result.

The sensitivity analysis reveals that for the sandy soils only one of the parameters considered, the SCS Curve Number, is critical. Runoff predictions on clay soils are sensitive to the Curve Number and to variations in FUL. Clearly how well the hydrology sub-model performs is highly dependent upon the selection of values for these parameters. Although Smith and Williams (1980) state that calibration of the sub-model is not necessary for specific applications, there is no doubt that better results than those presented here could be achieved if the model were calibrated using these two parameters. In reality, much firmer guidelines are required on the selection of parameter values than those contained in Knisel (1980). The user of the sub-model needs to have a 'feel' for the meaning of the Curve Number values in relation to a given study area. Without this, there is a danger of the predicted runoff values being seriously in error.

Because of the way in which the sub-model is constructed, the hydrological simulation is a poor representation of the hydrological cycle. When operated on a daily basis, the sub-model is essentially a storage model; yet it begins by receiving the rainfall input and calculating the runoff. The excess rainfall is then distributed among evapotranspiration, soil water storage and deep percolation. This approach is philosophically unsatisfying because runoff is usually viewed as the excess rainfall after the components of evapotranspiration, interception, soil water and groundwater have been filled. The only link between the simulation in the sub-model and this process is that soil water storage is estimated after each day's rainfall and the resulting value is used for the calculation of runoff from the rainfall received on the following day.

THE EROSION SUB-MODEL

The results of the preliminary trial of the erosion sub-model have been presented elsewhere (Morgan, 1980b) and only a summary is given here. Two files are required to operate the sub-model: a hydrology pass file and an erosion parameters file.

The hydrology pass file can be created as output from the hydrology sub-model or constructed afresh using observed data. The latter policy was followed in this case. Observed daily rainfall totals were used. Values for the EI_{30} index were calculated from rainfall intensities derived from autographic rain gauge charts according to the method of Wischmeier and Smith (1978, pp. 50-51). The observed runoff values were converted into depths using the 1 m^2 strategy outlined earlier. The excess rainfall or peak runoff was derived using a hydrograph procedure (Morgan, 1980b, pp. 5-6). Selection of values for the erosion parameters file is discussed in Morgan (1980b) and no further comment is made here.

Output from the sub-model separates the predictions of soil loss by overland flow from those by channel flow. Because the predictions of soil loss by overland flow were too low for the major erosion events, an arbitrary threshold of observed storm soil loss of 1 t ha^{-1} was introduced when analysing the results. Where the observed soil loss was less than this, the overland flow component of the sub-model was used to predict erosion. Where the observed soil loss equalled or exceeded the threshold value, the overland flow and channel flow components were combined to give the predicted value.

When the predicted soil loss values were derived in this way a significant correlation was obtained between them and the observed values for 31 storms ($r = 0.87$; $p < 0.001$). The slope of the regression line for predicted against observed values was 0.926. This result can be considered satisfactory. It also provided some pointers for further research on soil erosion on hillslopes. Doubts were cast on the validity of the separation of overland flow and channel flow adopted in the model. The possibility was raised that local concentrations of flow within the overland flow might be better considered as incipient channels rather than as part of the overland flow, even though no visible channel is being formed. Some justification for this approach is provided by the apparent importance of whether or not a threshold value of soil loss is exceeded in determining total storm soil loss. The threshold value of 1 t ha^{-1} is a crude indicator of sediment concentration. The latter has been shown by Savat (1979) to be a determinant of whether or not channel formation, i.e., rilling, occurs.

IMPLICATIONS

The hydrology sub-model can be looked at in two ways: as a runoff predictor and as input to the erosion and chemistry sub-models. In the first case, the decision on the value of the SCS Curve Number is critical to the success of the sub-model as a predictive tool. The results of this preliminary trial, although giving poor correlations between predicted and observed runoff volumes, suggest that better predictions could be achieved with calibration. The results also show that overall the sub-model performs better with respect to 'observed' data determined on the 10 m^2 than on the 1 m^2 basis.

Unfortunately, the study also shows that the erosion sub-model gives reasonable predictions of soil loss if the runoff values used as input are converted into depths on the 1 m^2 basis. The differences in 'observed' runoff depths between the two strategies therefore become critical. Sediment concentrations are calculated in the erosion sub-model from runoff depths, so that if runoff predictions from the hydrology sub-model are underestimated, then sediment concentrations will be underestimated and, consequently, soil loss will be grossly underpredicted. This would clearly happen here, for example, if the runoff predictions from the hydrology simulation for the 10 m^2 'observed' data strategy were used as inputs to the erosion simulation.

It should be stressed, however, that the CREAMS model is designed to operate with runoff depths averaged over a given catchment area. The distinction between the 1 m^2 and 10 m^2 strategies does not imply criticism of the model but is merely a question of how field measurements of runoff volumes from unbounded plots should be regarded with respect to catchment area. Although it might be argued that this problem would not arise if data from bounded plots were used, the results from the two strategies adopted in this study, together with the apparent independence of observed runoff and catchment area, must also cast doubt on what data from bounded plots really mean. It is the effective runoff generating area within the plot that needs to be known, not the total plot area, if meaningful observed data are to be obtained and meaningful predictions made.

CONCLUSIONS

If this study is viewed solely as an exploratory investigation into the application of the CREAMS model, the results can be considered promising. Reasonable predictions of soil loss are obtained provided that: (a) the concept of channel erosion is extended to include convergences of flow within the overland flow whenever sediment concentrations exceed a critical threshold; and (b) observed runoff depths from unbounded plots are calculated with the 1 m^2 strategy. The hydrology sub-model shows promise as a runoff predictor if the observed runoff is calculated with the 10 m^2 strategy and better guidelines can be established for determining SCS Curve Number values.

Work over the next two years will concentrate on resolving the problems of matching the hydrology and erosion sub-models and on improving the guidelines for the selection of parameter values. From this research it will be possible to determine the suitability of the model to UK conditions. Although the model specifies application to agriculture, it is of particular interest to determine whether, through careful selection of parameter values, it can be adapted to cover woodlands, moorlands, grasslands, reclaimed mining land and recreational areas. In this way the CREAMS model could be used to predict runoff, sediment and chemical pollution from most rural land utilisation systems within the UK.

ACKNOWLEDGEMENTS

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APPLICATION OF THE CREAMS MODEL AS PART OF AN OVERALL SYSTEM FOR OPTIMIZING ENVIRONMENTAL MANAGEMENT IN LITHUANIA, USSR: FIRST EXPERIMENTS*

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INTRODUCTION

Models are widely used to study nonpoint source pollution from an individual field. However, many problems exist on a higher spatial hierarchical level, e.g., a farm, watershed, or region, the analysis of which requires appropriate mathematical models. However, few existing models adequately describe regional or watershed problems of natural resources utilization and/or environmental management, therefore there is a clear need for better elaborated field-level models which can be used to solve regional problems. This paper presents the first application results of such an approach, namely the utilization of the CREAMS model (Knisel, 1980), to examine the problem of optimization of natural resources, and environmental management and protection for the Lithuanian Soviet Socialist Republic.

CONCEPTUAL SCHEME OF AN OVERALL MODEL OF OPTIMIZATION OF NATURAL RESOURCES UTILIZATION AND ENVIRONMENTAL MANAGEMENT OF THE LITHUANIAN REPUBLIC

For the optimization of natural resources utilization of any region, first of all the following general, interrelated objectives should be considered:

- to elucidate the optimal dynamic correlation between the branches of the economy in such a way that implementation of certain economic measures would enable rational utilization of the resources of a region;
- to ensure a highly profitable, balanced and stable development of industry, agriculture, forestry and water management;
- to create an optimal environment for man.

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For Lithuania, the Overall Model of Natural Resources Utilization and Environmental Management (OMNRUEM) is based on the three following considerations. A schematic representation of the model is shown in Figure 1.

A. Spatial arrangement of the territory with respect to the maximum production output. This tendency is revealed when analyzing the following data:

1. Historical trend of the land use in the past.

2. Twenty to thirty year forecasts for those branches of the economy which are of paramount importance in the transformation of the given territory, i.e., agriculture, forest and water management, branches of industry which change the environment, and urbanization processes.

The analysis of land utilization is developed in the Model of Intersectoral Optimization of Land Use (MIOLU). Its objective function is an allocation of the branches over the territory in such a way that the national requirements in production might be met optimally. Requirements for individual sectors are ranked by introducing coefficients of production preference.

In the Lithuanian Research Institute of Forestry's model of interbranch optimization, forest allocation is given by L. Kairiukstis and S. Mizaras. Its objective function and principal constraints are as follows:

$$\sum_{i}^{m} \sum_{j}^{n} c_{ij} \quad x_{ij} \rightarrow \max$$

$$\sum_{i}^{m} x_{ij} \leq a_j$$

$$\sum_{j}^{n} c_{ij} \quad x_{ij} \geq p_i k_i$$

$$x_{ij} \geq 0$$

where c_{ij} is a productivity of i branch in j land units in roubles/ha;

x_{ij} is i branch area in j land units, ha;

a_j is j land area, ha;

p_i is a requirement in i branch production, in roubles;

k_i is a coefficient of requirement correction;

m is the number of economic branches;

n is the number of land unit types.

Introduction of additional constraints in the model account for the possibilities of meeting the requirements, and their preference, as well as application of simulation models which will enable us to evaluate the

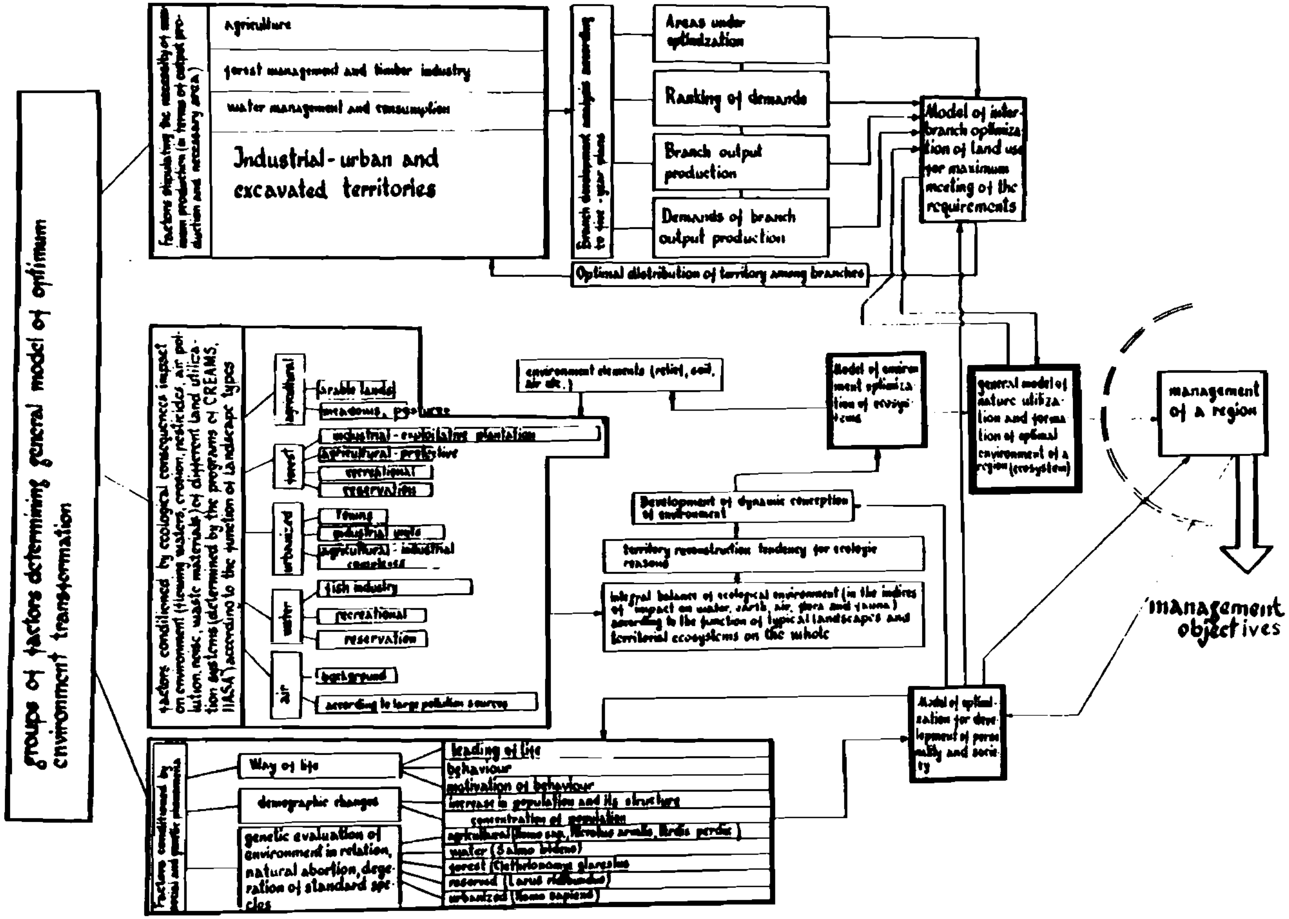

Figure 1. Scheme of overall model of natural resources utilization and environmental management of a region

alternatives for distribution of different types of forests in the system of interbranch land use of a region.

B. Territorial transformation for ecological reasons. The following main items are analyzed:

1. Ecological impacts of management systems on agricultural landscapes. Such an estimation is carried out according to the main soil and relief types as well as for individual types of land use, like cropland, meadows and pasturelands.

2. Ecological impacts of management systems on forest landscapes. The evaluation is carried out separately for each sector of the forest according to its principal use: production of wood, protection of agricultural land, recreation, preservation of nature.

3. Ecological impacts of industrial and urbanized territories on the environment (air and water pollution, noise, etc.). The assessment is fulfilled in conformity with the function and categories of the landscape. Large towns, single industrial sites and large industry-like agricultural complexes are assessed separately.

For the assessment of ecological impacts of management systems in accordance with the three items mentioned above (Knisel, 1980; Fritts, 1977) the territory is divided into large landscape types in keeping with geomorphological and soil patterns. For such an assessment, simulation models are used, including slightly revised submodels of the CREAMS system. Air pollution and its impacts on ecosystems are determined for a number of components (gaseous and aerosolic additions, heavy metals, radioactive and carcinogenic substances, etc.) both for large landscape categories and for the Republic on the whole.

Cyclic, long-term climatic oscillations caused by solar-earth relations which affect stability and productivity of ecosystems are ascertained by dendrochronological methods, using tree-ring data (Kairiukistis, 1981; Fritts, 1977). Cyclic climatic fluctuations are introduced in the Overall Model by means of increase or decrease in bounds of unfavourable impacts on the environment. All aspects of the analysis indicated in item B are realized in the Model of Optimization of Environmental Management (MOEM).

C. Territorial transformation in the interests of man. This trend is analyzed by the Model of All-round Development of Personality and Society (MADPS). It is comprised of two submodels describing genetic and social issues. The following phenomena are studied:

1. Impacts of radioactive and chemical mutagens circulating in the environment. Investigations are carried out on a large scale on indicatory species, including man, in different landscape categories. Simulating the effects at different levels of exposure will reveal the possible consequences of such impacts.

2. Feedback impacts of social and demographic changes on environmental transformation. Simulation of genetic and societal impacts is found to be the basis for the selection of permissible parameters of man's influence on the environment at which the development of personality, population and society is not infringed upon.

The analysis of the above stated trends stipulates a dynamic concept of optimal environment. On this basis an optimal development of different branches of the economy in the given region is determined with respect to time, and parameters of the transformation of the territory are elaborated. The output from the Overall Model is analyzed by decision-making bodies of the Republic and then it is used as a basis for the models describing development of the main sectors of the economy related to natural resources utilization (Kairiukstis, 1981). In such a way, agricultural, urban, recreational, forest, and other landscapes harmoniously form optimal development of the environment and rational utilization of productive forces and natural resources of the region (Kairiukstis, 1979).

In the overall model, the most attention is focused on man: on the one hand, demographic changes increase the material and spiritual requirements of micropopulations and society, on the other, industrial, urban and agricultural development has adverse impacts on the conditions of man's life. To avoid contradictions of the above mentioned factors in the overall model, the delivery of data on optimum territory distribution in conformity with the prevailing functions is foreseen. For Lithuania, preliminary analysis of the territorial transformation trends stipulated by production, as well as by ecological and social consequences of this production has led to approximate values of optimal land use.

The following typical conditions describe the role and place of separate territories in the landscape structure of Lithuania (Figure 2):

- average population density is 51 persons/km^2;
- well developed industry (more than 60% of national income);
- high level of land transformation (55% of farmland is covered with closed drainage; wide network of roads (0.5 km/km^2); on the area of 6.5 million ha there are two large (400,000 people) and 10 small (about 100,000 people) towns;
- intensive agriculture with dairy cattle (average cereals yield is 2.5 tonnes per ha; average annual yield of milk from one cow is 3500 kg; that of meat is 12.5 tonnes per 100 ha of farmland);
- traditionally developed complex silviculture which meets approximately 75% of the Republic's requirements of wood (average area of a forest is 3,000 ha; forest management units are 30,000 ha with one forester per 900 ha);
- well organized nature preserves, intensively developed recreational activities such as hunting.

In accordance with the aforementioned analysis, agricultural lands should occupy 55-57% (including 17% of meadows and pastures), forest areas, 30-33%, water and wetlands, 5-6%, industrial and urbanized areas, 5-7%, of the territory of the Republic. Forest and agricultural territories, apart from their direct functions, occupy lands meant for other purposes as well, and must fulfill auxiliary functions.

Contiguous boundaries are being determined and the scale of mutual overlap of the territories with different functions will allow buffer zones between the main sectors of the national economy to be established. The buffer zones

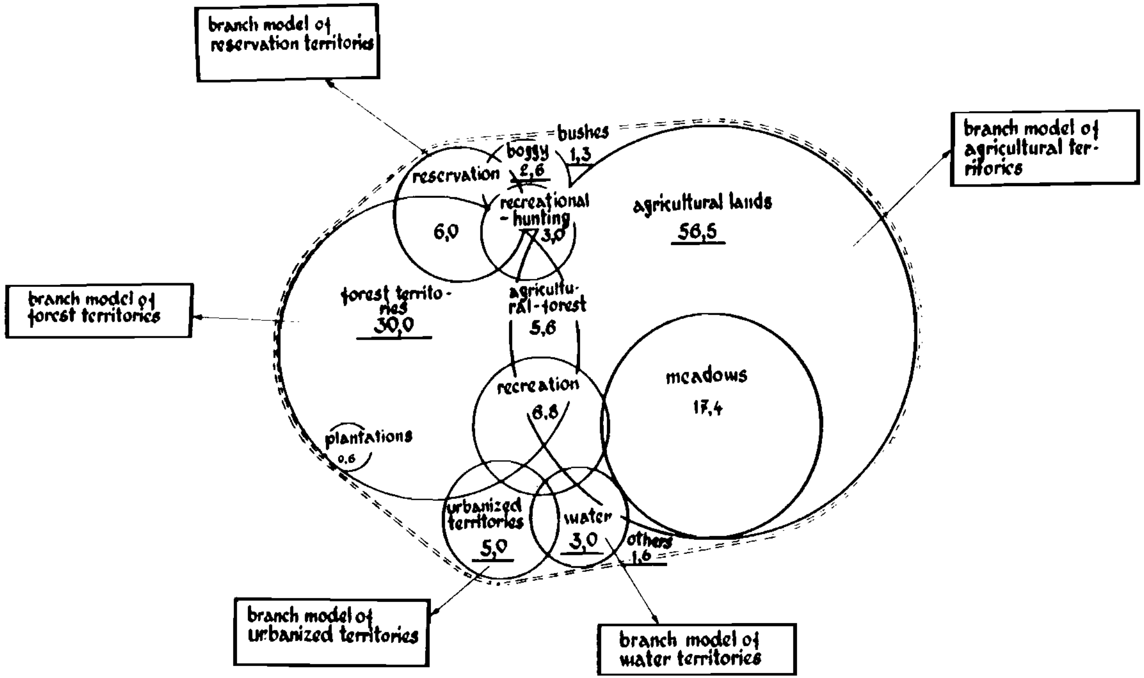

Figure 2. Scheme of Lithuania's ecosystem, with territory distribution according to function (%)

in optimal regional development have mixed functions, in accordance with the main overlapping economic sectors. The forestry sector, for instance, on concrete territory becomes greatly specialized under the pressure of agricultural, recreational, industrial-urban and other sectors. Other sectors, e.g., agriculture, water management, etc., are optimized conformably under the pressure of contiguous economic branches. Thus, adverse mutual impacts of the competing functions (production, recreation, preservation) is avoided and sectoral models are determined more precisely.

Sectoral models are territorially differentiated models of the development of concrete landscape categories: for instance, the agricultural-industrial territories of Middle Lithuanian lowland; the agricultural-recreational territories of preservation and recreational zones; industrial-exploitative forests; the agricultural-protective forests; the recreational forests, etc. The sectoral models determine parameters of economic development, and utilization and reproduction of natural resources. They also serve for the correction of the overall model of the Republic and for long-term planning of individual sectors of the national economy. The sectoral models do not reflect the prevailing function of a concrete territory. Nevertheless, the models of territorial control together with the sectoral models are prefectly appropriate to look into the function of concrete geographical landscapes. They determine programs of natural resources utlization and their development as well as programs of environmental management. A sectoral model of forest territories is shown in Figure 3.

GENERALIZED TERRITORIAL LANDSCAPE UNITS FOR ECOLOGICAL EVALUATION OF THE IMPACTS OF MANAGEMENT SYSTEMS ON THE ENVIRONMENT

Assessment of the impacts of management systems on the environment is made by the MOEM model. However, these impacts cannot be evaluated for the region as a whole. It is necessary therefore, to divide the territory into the generalized elementary units which differ in relief, soil types, and vegetation. It is assumed that the territorial units would have certain specific reactions to the management systems and that for different units the reactions would be different too. Besides, the generalized constituent territorial units are more quantifiable and description of their representativeness relative to the optimized territory is easier.

For experimental generalization, the Utena administrative region was chosen. It is situated within the Baltic hills with an uneven lacustrine-hilly morainic landscape. In the region, podzolic sandy and sod-podzolic loamy soils of medium or poorly developed podzolization process prevail. Total area of the territory is 121,925 ha, including 65,807 ha of farmlands, 5,619 ha of water, and 36,054 ha of forest. Approximately 45% of the farmland soils are eroded.

In this territory, seven profiles 5-10 km in length have been taken on the recommendation of Prof. A. Basalikas. The profiles reflect the most characteristic features of the region. The profiles were processed by Mr. I. Milius in such a way that the lines were broken and always passing in the direction of water flow. A field profile is shown in Figure 4. On the broken line of the profile obtained, predominant soil type, kind of land use, length and average slope between the two points from one breakpoint to the next have been noted. Total length of the selected profiles is about 50 km, on which 1040 elementary landscape units were delineated. Average slope of a territorial elementary unit was found to be 3.844% ± 0.144% with the

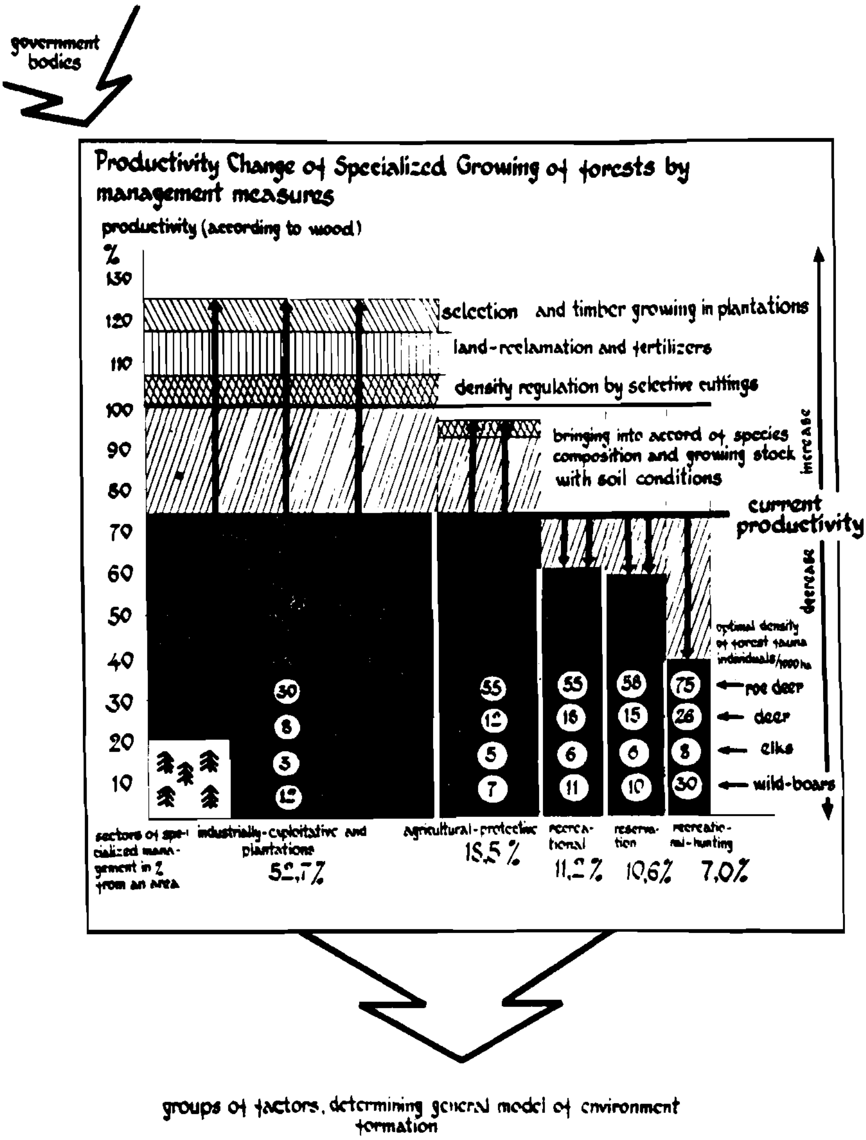

Figure 3. Sectoral model of forest territories

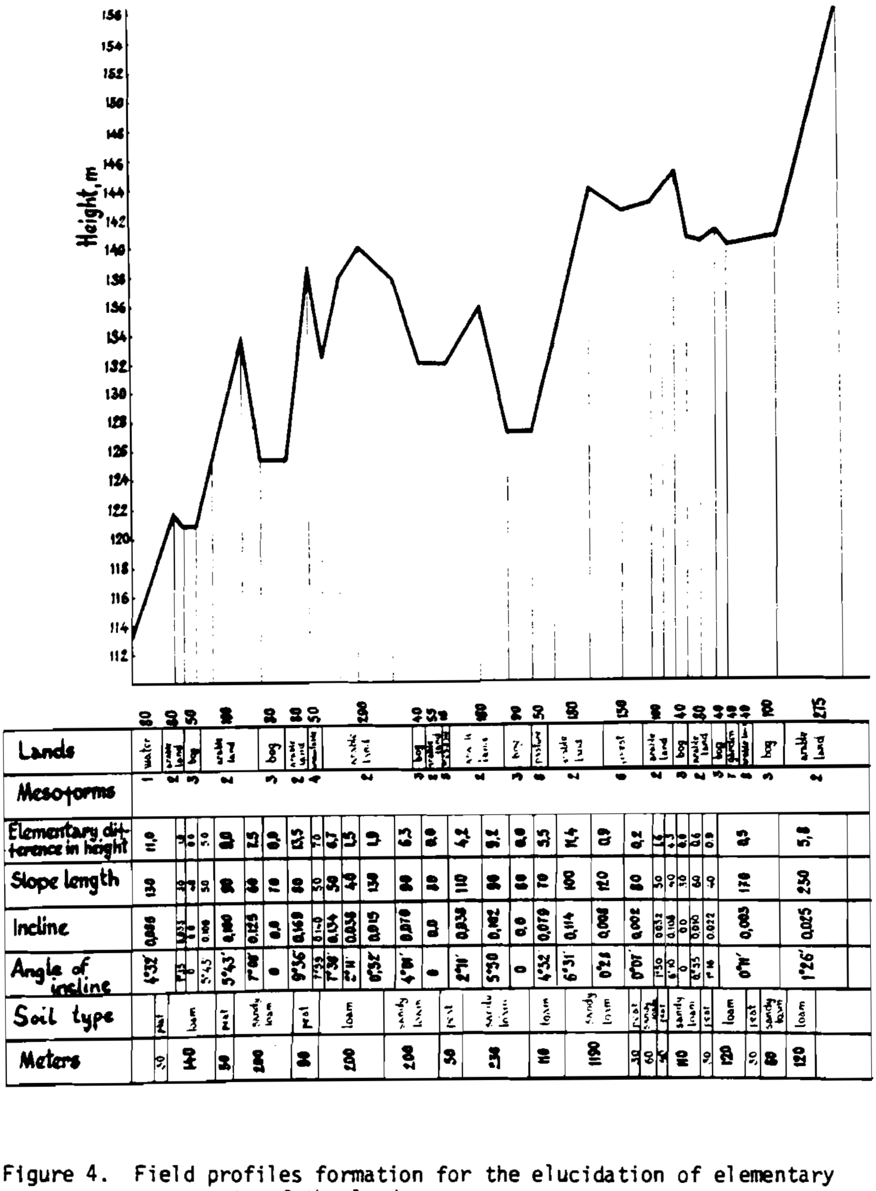

Figure 4. Field profiles formation for the elucidation of elementary components of the landscape

coefficient of variation for a single measurement 0.97. The mean length of the elementary unit is equal to 70.5 ± 2.1 m with a coefficient of variation 0.75. The values are given for the 0.95 confidence level.

TESTING THE CREAMS MODEL FOR A COMPARATIVE ASSESSMENT OF THE IMPACTS OF MANAGEMENT SYSTEMS ON THE ENVIRONMENT

A preliminary study of the CREAMS model has shown us that it may be one of the principal tools in the Model of Optimization of Environmental Management (MOEM). As the first step, CREAMS was run with the data of a small (Davila) watershed in the Utena region (during L. Kairiukstis' stay at IIASA, March 1980). The conclusion was that the model is applicable for thorough analysis of hydrological and hydrochemical phenomena in small watersheds of Lithuania. Also, it was assumed that the model could be used for analysis of processes in more complex ecosystems.

During L. Kairiukstis' second visit to IIASA in November 1980, it was decided to use CREAMS for the whole Utena administrative region.

Data on soil hydrologic conditions were collected by the Department of Geography of the Lithuanian Academy of Sciences and by the Lithuanian Research Institute of Forestry for three prevailing soil types: loam, sandy loam and peat. Soil samples were taken on slopes of different steepness and length. The dynamics of leaf surface of the typical vegetation (barley, perennial grasses, forest) have been studied by the scientists of the Botanical Institute of the Lithaunian Academy of Sciences and the Lithuanian Research Institute of Forestry.

Results from the Hydrology Model

Computations have been performed using the hydrology model, Option 1 based on daily precipitation. Precipitation data was taken from the Utena meteorological station and it was assumed to represent the whole region. The runs were made for the period 1972-1980 for the soil and vegetation types shown in the following table.

Vegetation Type	Soil Type		
	Loam	Sandy Loam	Peat
Barley	x	x	x
Perennial Grasses	x	x	
Spruce-Deciduous Forest	x		
Spruce Forest		x	
Pine Forest		x	
Black Alder Forest			x

The given soil and vegetation types predominate in the Utena region. Annual components of the water balance obtained from simulation are presented in Figure 5. The given period was notable for significant fluctuations of annual precipitation representing both quite dry and wet years. Moreover, precipitation values for 1979-1980 were taken considerably higher than they were in reality, so that the whole possible range of precipitation was actually covered.

The outputs obtained show different hydrologic conditions depending upon the soil type. For example, Figure 6 illustrates a relation of surface runoff and precipitation on loamy soils. It is practically the same for perennial grasses (of the first year sowing) and barley, but different for a spruce-deciduous forest.

After obtaining the data on water balance components for typical landscapes, a problem arises--determining the water balance components for the whole region. It should be noted that in the CREAMS model, water balance components depend upon the land use type and soil mechanical composition but not on the area and land slope.

Water balance components for the whole region were calculated in accordance with the distribution of its area into soil and land types (Table 1). It was determined that mean yearly evapotranspiration from forest lands is 507 mm, while surface and subsurface runoff comprise 190 mm. Average evapotranspiration and runoff from agricultural lands amount to 486 mm and 211 mm, respectively. Evaporation from water surface is calculated to be 678 mm, while that from towns, roads, etc., approximately makes up 226 mm.

For the period of 1972-1980 mean annual evapotranspiration for the whole Utena region was found to be 493 mm and runoff (surface and subsurface) was 204 mm. In 1969, I. Jablonskis calculated water balance of the region on the basis of direct measurements of runoff and precipitation. Evapotranspiration value according to our calculations is higher by 4% and runoff is lower by 12% as compared with Jablonskis' results. It must be noted that the period taken by Jablonskis had slightly higher total precipitation. Consequently, the results of water balance calculations for quite a large region using the CREAMS model are quite acceptable. Particularly reassuring is the fact that the model is apparently applicable for territories with stable snow cover typical of Lithuania.

However, slight discrepancies in calculated values of transpiration and runoff are apparently related to poor performance of the model for winter conditions. In Lithuania, air temperature is below 0^{o}C during November-March while the model takes it as equal to 0^{o}, therefore an increase in computed evaporation values is obtained.

Results of the hydrologic component of the CREAMS model for the Utena region leads us to the following conclusions:

1. The hydrologic submodel is quite acceptable for computations of water balance components both for elementary landscape units and for large territories.

2. For the conditions in the Baltic area, the algorithm of computations of water balance components must be improved for air temperatures below 0^{o} C.

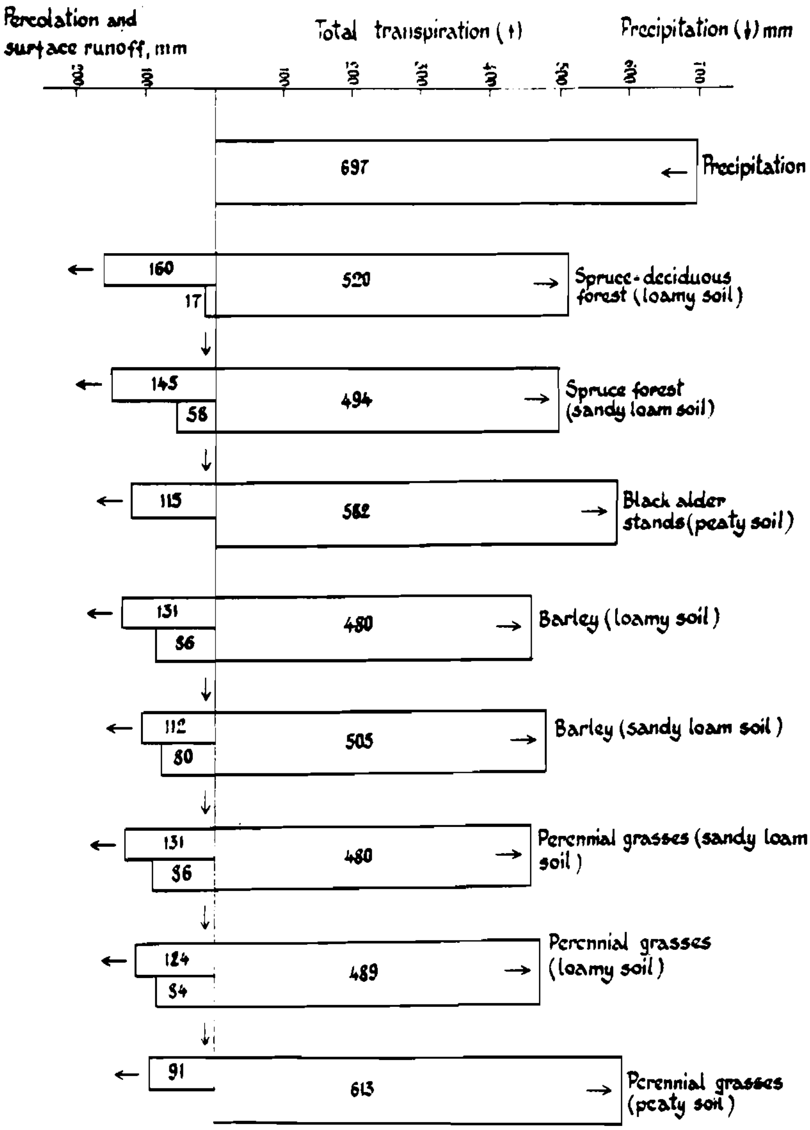

Figure 5. Average annual components of water balance in water catchment areas with different soils and lands (in the Utena region) for the period 1972-1980 (in mm).

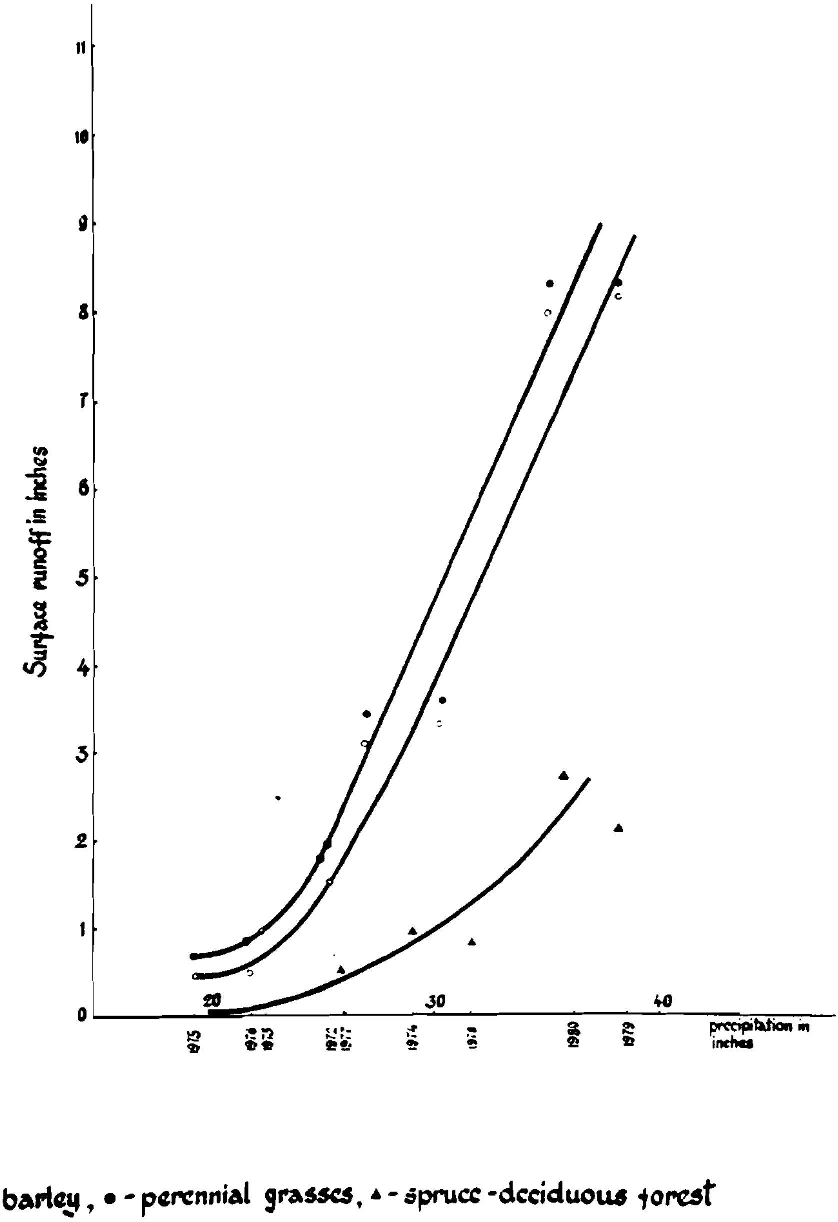

Figure 6. Calculated surface runoff in different years according to precipitation quantity, in elementary water catchment areas on loamy soils covered with barley, perennial grasses and spruce-deciduous forest

Table 1. Representation of separate elementary components of landscape in acres (according to slope % and slope length in feet) of the Utena region, Lithuanian SSR

Interval of slope length in m	Interval of slope steepness in degrees / Mean steepness slopes in % / Mean slope length in feet	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	Total area in acres	Percent of area in a slope
	Mean steepness slopes in %	1.11	3.33	5.56	7.78	10.00	12.22	14.44	16.67	18.89		
		Area in Acres										
0 - 44.7	103.7	7160.8	2952.9	1624.1	885.9	516.8	442.9	147.7		73.8	13804.9	0.2
44.7 - 63.2	179.7	17053.1	7529.9	7308.5	4207.9	1771.8	1771.8	221.5		664.4	40528.7	0.7
63.2 - 77.5	232.0	4798.5	6644.1	6644.1	2583.8	1476.5	738.2	369.1	1107.3	369.1	24730.6	1.2
77.5 - 89.4	274.5	9818.4	2067.0	2583.8	1033.5	4650.8	516.8	516.8	-	-	21187.2	1.7
89.4 - 100	311.2	19932.2	8637.3	7308.5	2657.6	1328.8	664.4	-	-	-	40528.7	2.2
100.0 - 109.5	344.1	-	-	-	-	-	-	-	-	-	-	2.7
109.5 - 118.3	374.1	3838.8	5758.2	2879.1	-	-	-	-	-	-	12476.1	3.2
118.3 - 126.5	401.8	6644.1	3322.0	3322.0	3322.0	-	-	1107.3	-	-	17717.5	3.7
126.5 - 134.2	427.8	5020.0	5020.0	1255.0	1255.0	2510.0	-	-	-	-	15059.9	4.2
134.2 - 141.4	452.2	4207.9	1402.6	1402.6	1402.6	-	-	-	-	-	8415.8	4.7
141.4 - 148.3	475.4	-	-	-	-	-	-	-	-	-	-	5.2
148.3 - 154.9	497.6	16979.2	-	1697.9	167.9	-	-	-	-	-	20375.1	6.7
154.9 - 161.2	518.7	3691.1	-	3691.1	-	-	-	-	-	-	7382.3	6.2
161.2 - 167.3	539.1	-	-	-	-	-	-	-	-	-	-	6.7
167.3 - 173.2	558.7	6422.6	-	-	-	-	-	-	-	-	6422.6	7.2
173.2 - 178.9	557.7	-	-	-	-	-	-	-	-	-	-	7.7
178.9 - 184.4	596.0	9744.6	7308.5	2436.2	2436.2	-	-	-	-	-	24361.5	8.2
184.4 - 189.7	613.8	-	-	-	-	-	-	-	-	-	-	8.6
189.7 - 195	631.1	2731.4	-	-	-	-	-	-	-	-	2731.4	9.1
195.0 - 200	647.9	28790.9	-	2879.1	-	-	-	-	-	-	31670.0	9.6
		146833.5	50642.4	47468.1	21482.4	12254.6	4134.1	2362.3	1107.3	1107.3	287,392.1	

3. For the conditions of the Baltic area, special investigations on accuracy of computations should be carried out for periods with snow cover, including spring melting and for frozen soils with different moisture.

4. The CREAMS model does not take into account the influence of the high groundwater level on evaporation and runoff which is sometimes typical of the Baltic area conditions. It is necessary to analyze what errors are associated with disregarding this phenomena. In the case of considerable errors a corresponding submodel should be elaborated and included in CREAMS.

Results from the Erosion Model

Computation of soil erosion has been performed for the period 1972-1980 as well. Simulations were made for overland flow on uniform slopes. The runs were for the following elementary landscape units (slope steepness in % is indicated in the numerator, slope length in m. is in the denominator) (Table 2).

Table 2. Elementary landscape units

Barley	Perennial grasses	Spruce-deciduous forest	Spruce forest
	Loamy Soil		
4/40 4/88 4/145	4/88		
8/4/ 8/88 8/145	8/88	8/88	
12/40 12/88 12/145	12/88	12/40 12/88 12/145	
14/40 14/88 14/145	14/88	16/88	
	Sandy loam soil		
4/88	4/88		
8/40 8/88 8/145	8/88		8/88
			11/40 11/88 11/145
			16/88

Computed mean annual values of soil erosion are presented in Table 3 (in tonnes/hectare per year)*.

*For easy reference the data in Table 3 has been aligned exactly to match that of Table 2.

Table 3. Mean Annual Values of Soil Erosion

Barley	Perennial grasses	Spruce deciduous forest	Spruce forest
	Loamy soil		
1.85 2.00 1.93	1.01		
3.80 3.98 4.25	2.89	0.42	
6.30	5.28		
8.20 8.74 8.99	6.55		
		0.35	
	Sandy loamy soil		
1.80	1.06		
2.82 2.89	1.95		
			0.49
		1.01	2.39

Relation between the total 9-year erosion and slope steepness for different land units on loamy soils is given in Figure 7. The relation is linear and the dispersion of the results on land units is insignificant. Mean annual value of soil erosion for average slope in the region is about 2 t/ha. The influence of slope length on erosion is less than that of steepness.

The results of computations have illustrated the stabilizing role of forests in erosion processes on loamy and sandy loam soils. For instance, on slopes covered with spruce-deciduous forest on loamy soils, noticeable erosion begins only with slope steepness of 6-8% (Figure 8). The erosion over 2 t/ha per annum is typical of steep (11-13%) wooded slopes. It comprises one fifth of the erosion from a field covered with perennial grasses*. Annual erosion value closely depends on total precipitation (Figure 9) sum. In dry years (1973, 1975) erosion practically is not observed, while in rainy years (1979, 1980) it significantly increases and becomes noticeable even on the slopes covered by forest.

The results of the erosion model have confirmed its applicability forstudying soil erosion processes in different soil and hydrologic conditions, with different slope steepness, in different types of land use, etc. It is necessary now to pass from computations of somehow conditional data to those of real slope and real types of surface runoff. Before starting similar computations for the Utena region, it is necessary to solve a number of methodological problems. Another methodological aspect of utilization of the erosion model of the CREAMS is the study of the model's applicability to the

*Total erosion values should be slightly over those observed as precipitation for 1979-1980 was taken to be higher than that observed.

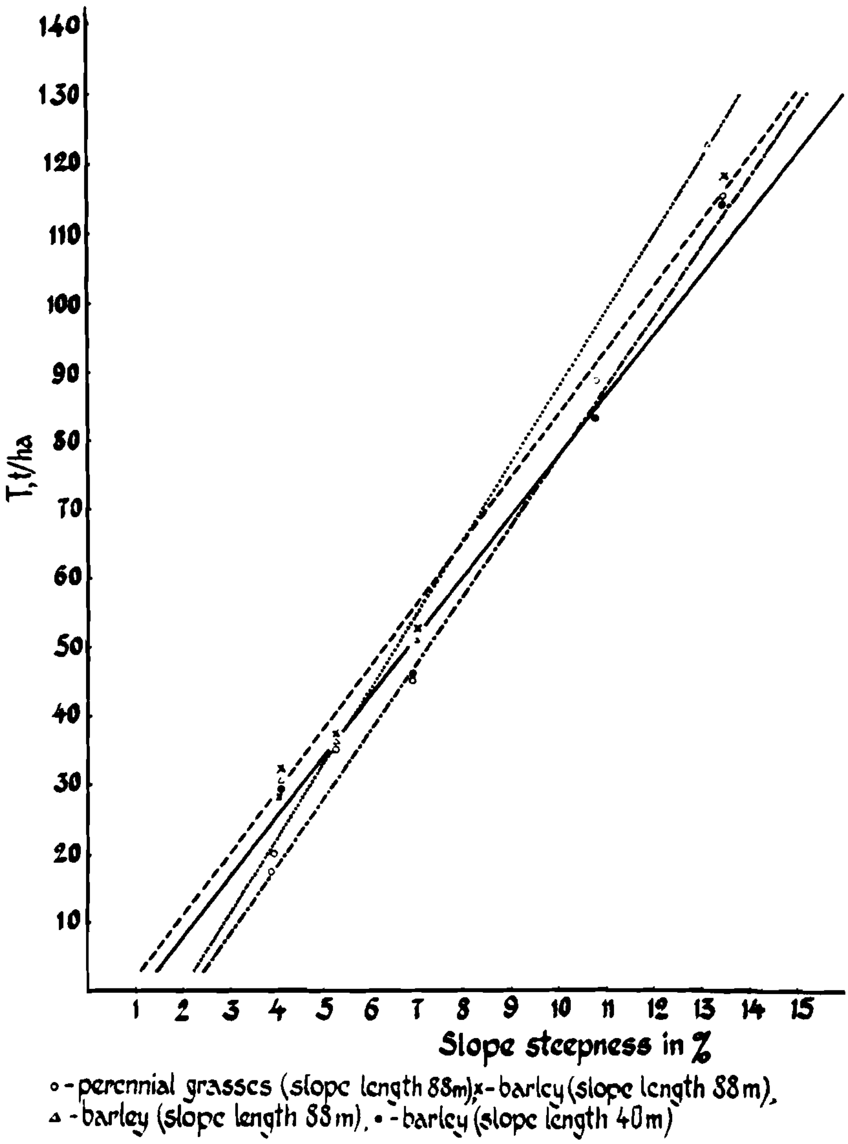

Figure 7. Total quantity of erosion (T) products of loamy soils depending upon slope steepness

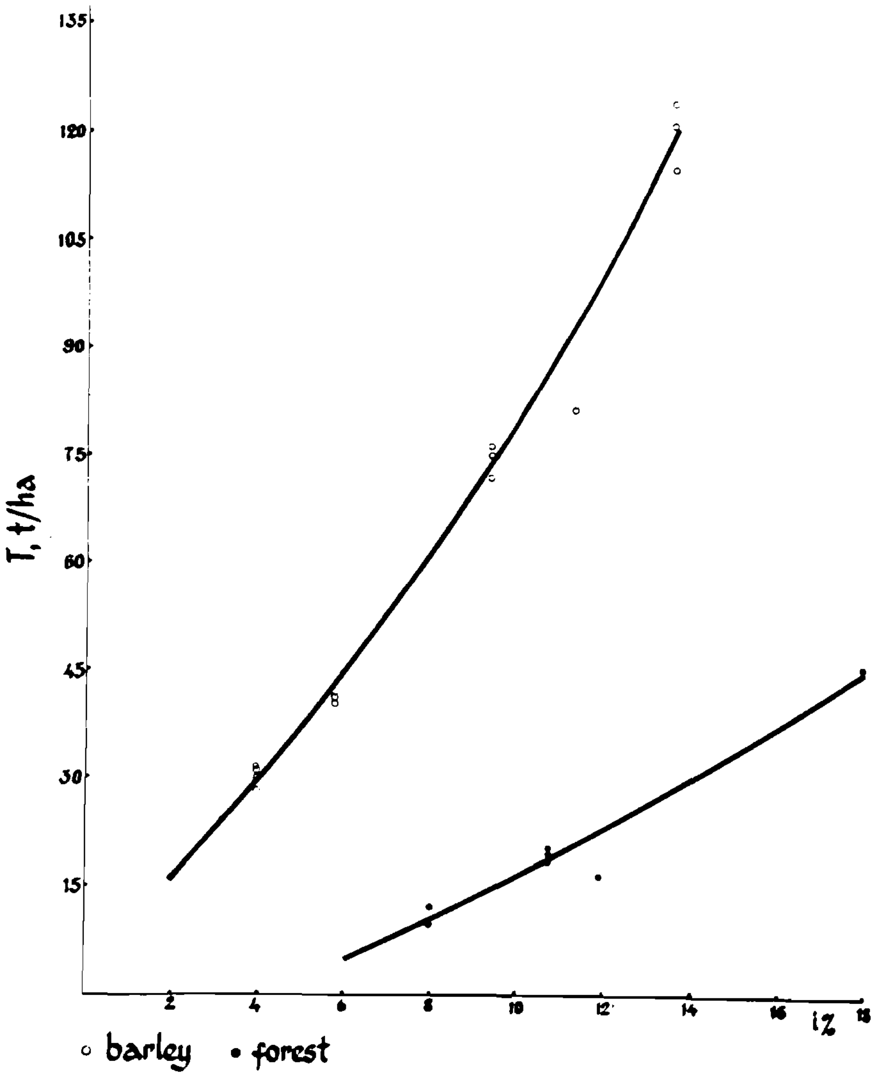

Figure 8. Mean quantity of eroded soil(T) (1972-1980) on slopes of different steepness, with loamy and sandy loam soils, covered with barley and spruce-deciduous forest

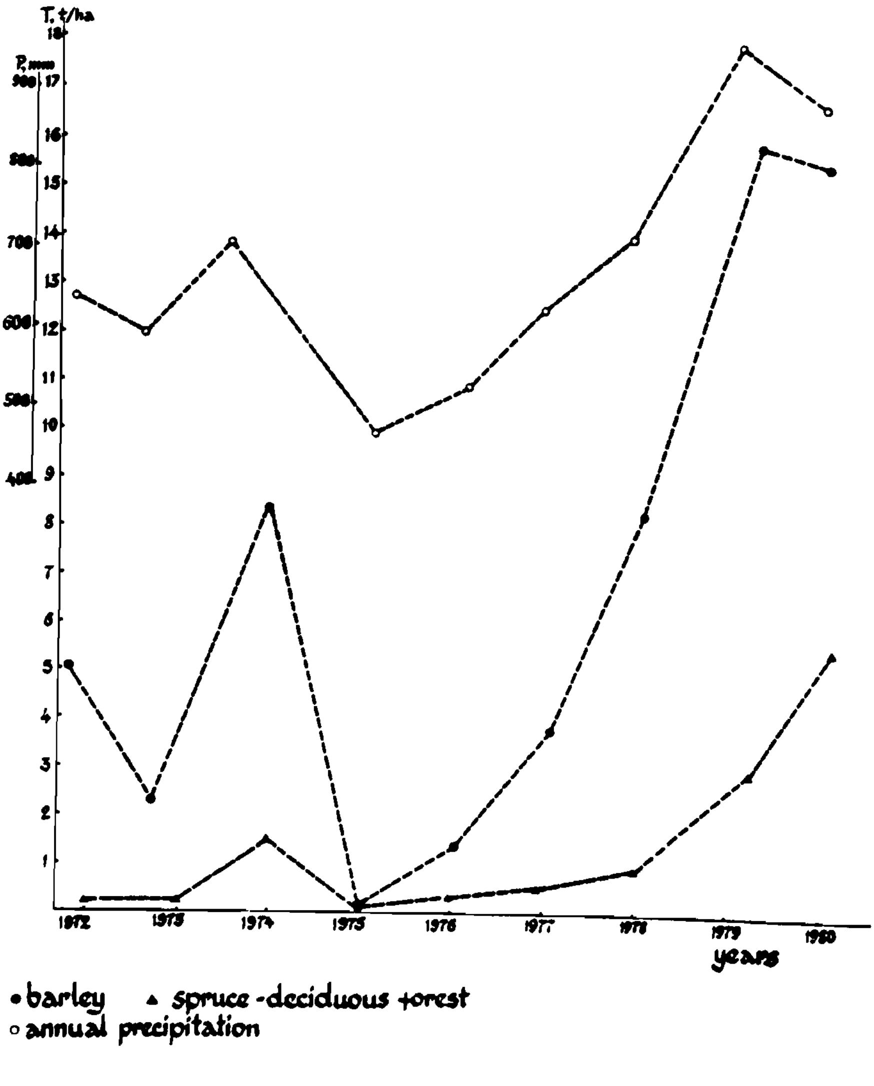

Figure 9. Intensity of eroded soil (T) in different years according to precipitation (P) in elementary water catchment areas of 8% steepness with loamy soil, covered with barley and spruce-deciduous forest

computations of soil erosion during spring snowmelt. Finally, verification of computations by experimental data is required.

Results from the Nutrient Model

The model describing nitrogen and phosphorus behaviour was applied for loamy soils only on slopes of 8% covered with barley and spruce forest. In this application, the results of simulation are of limited interest. Nevertheless, a definite inference from the computation can be drawn on the methodology.

The values of nitrogen and phosphorus (in kg/ha per annum) removed from soil for 1972-1980 and 1972 (in brackets) are presented below:

Chemical element	Vegetation	Removed by surface runoff	Removed by sediment	Removed by percolation
Nitrogen	Barley	0.65 (0.34)	2.04 (1.03)	14.15 (43.74)
	Spruce forest			20.2 (21.40)
Phosphorus	Barley	1.95 (0.98)	5.25 (2.63)	
	Spruce forest	-	-	-

The fact that in a moderately dry year (1972) and during the whole period calculated (1972-1980), nutrients removal by surface runoff and by sediments takes place only from the agricultural field and does not occur from spruce forest, in particular attracts our attention. The decreased values of the nutrients removed from the forest are therefore understandable.

For the time being, it is possible to conclude that the nutrients model may be a convenient means in the aforementioned overall system of models. On the one hand further adjustment of the model to solve regional problems and on the other its verification with the data of local experimental observations are necessary. This model (as well as other parts of CREAMS) require further investigations on its applicability for winter conditions with stable snow cover.

An attempt has been made to try the pesticides model using the data of the Davila watershed. However, the work has not been completed so far because of the difference of pesticide denominations in the USSR and in the USA, and the attendant difficulties of determining their breakdown properties before inclusion in the model.

CONCLUSION

The first experiments with the CREAMS model have shown us that it is adequate in general for the conditions of Lithuania. It is, therefore, worth using further, since the development of a new model would be much more costly. However, further application of the model causes Lithuanian experts various problems. The principal problems are outlined below.

1. Some outputs of the runs for single fields should be verified. It will require, in some cases, an organization of special additional studies.

2. The model has been developed on the data obtained in IIASA in natural conditions somehow dissimilar to those of Lithuania. These are long, stable snow cover, its melting and associated hydrologic, erosion and chemical processes. Hence, a thorough check of the model's adequacy is needed and, in case of negative results, development of a corresponding submodel should be carried out. Similar action would be necessary for conditions of shallow groundwater level.

3. Reasonable results have been obtained for forest land units, though CREAMS was not developed for forests. Apparently the work on adjustment of the model to forest conditions will continue, so that a new special system of models will be developed for which CREAMS would serve as the base.

4. The main content of this paper is an adjustment of a field level model to solve regional level problems. The runs of the hydrology and erosion models have brought quite reassuring results. It is expected that extensive methodological studies of CREAMS application for regional problems will be continued since optimal environmental management is one of the most important tasks in Lithuania.

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P A R T III

REVIEW OF CASE STUDIES
OF CREAMS MODEL APPLICATION

W.G. Knisel and V. Svetlosanov

Several scientists are to be commended for their diligent efforts in the application of the CREAMS model to real-world problems in their respective countries. Although CREAMS is a simple model in many respects, it is totally complex in interactions and with respect to readily available data. The model was developed in the United States, where more information was available to determine parameter values than in other countries.

Applications represented a range of operating conditions such as climate, management, and the level of modeling expertise. The case studies brought to light some model weaknesses (areas requiring improvement) as well as the potential benefits of model application. Some of the improvements currently are being made by the original modeling team and these are discussed in another section of this report.

One area of concern across the case studies was the effects of freezing temperatures. The present model permits some processes to continue when temperatures drop below 0° C and the processes cease. Discrepancies between model representation and actual conditions may cause less than satisfactory results. In this specific case, percolation will be in error, as well as underestimation of soil nitrate content, and overestimation of nitrate leaching. This in turn affects the overall nitrogen balance.

It was pointed out that CREAMS was developed for climatic conditions in the USA and rainfall energy in European areas probably is not as high as in the USA. This would lead to overestimation of soil detachment by raindrop impact. Storms in Western Europe generally are of longer duration, lower intensity and energy, and thus of lower erosion potential than in the United States.

Another problem identified was that of snowmelt. Unfortunately, there were some logic errors in the version of CREAMS that was used in most of the case studies. (The problem has been corrected in model version 1.7 presently operative at IIASA.) Basically, there were two problems: (1) the model did not consider precipitation as snow on days when air temperature was less than 0° C, and (2) there was a double accounting of soil water from melting snow, all of which infiltrated into the soil. These problems have been corrected in version 1.7, but the snowmelt subroutine continues to infiltrate most of the snowmelt. It has not been tested for extreme snowpack which may occur in the colder climates of Europe and Asia.

There were two types of applications made in the case studies: (1) site-specific where some data were available for model verification, and (2) generalized application for "average", or "typical", or "representative" situations. The two types require different degrees of parameter information. At locations where observed data are available from field experiments, such as the United Kingdom case study, much more detailed information generally are available or might be obtained from additional field observations, sampling, or laboratory tests. This may not be feasible or practical for generalized or representative application, as for example in the Swedish case study. Even in countries where vast soils data are available, there are often times problem areas with specific soils for which there is litttle or no data. In these situations, the best information is generalized data based on soil textural classification. For example, the U.S. Department of Agriculture, Soil Conservation Service (1981) has developed a guide for users as an aid to estimation of parameter values. The guide contains a U.S. Department of Agriculture textural classification chart (Frevert et al., 1955). With a knowledge of the sand, silt, and clay content as needed for the erosion component, the soil texture can be determined from the chart (Figure 1). From textural classification, information in Table 1 (England, 1970) can be used for physical soil properties to estimate model parameter values. The data in Table 1 represent mean values over a range of soils, but this is sufficient for generalized model application to consider management alternatives. Also to aid the user, SCS included a table (Table 2) which gives the range of effective saturated conductivity by hydrologic soil group (Musgrave, 1955). Table 2 is based upon minimum infiltration rate which is least when the soil is saturated. Table 2 can be used in two ways: (1) if saturated conductivity, or minimum infiltration rate, is known, the hydrologic soil group can be determined for estimating SCS curve number, or (2) if the hydrologic soil group is known, saturated conductivity can be estimated. These tables are very helpful for the user when site- or soil-specific data are not available. The values should not be used for model validation with observed runoff data. Generalized applications are made primarily to examine differences between management practices, and the mean values from Tables 1 and 2 are satisfactory for this purpose.

Some general comments concerning observations from applications and experiences with the CREAMS model are in order. First, CREAMS was developed as a state-of-the-art model, and the scientists who developed it recognized that it would not consider all problems. It was assembled from existing submodels, or readily modifiable components, to form a basic framework upon which improvements and comprehension would be improved. In many respects, CREAMS represents a concept of an approach in the assessment of complex nonpoint source pollution. CREAMS is a tool to aid in the professional judgement on management effects related to nonpoint source pollution. The model is not a predictive model in absolute quantity.

One overwhelming observation has been made from experienced applications: the "average" condition or system is not the case where nonpoint source pollution is a problem. That is, some extreme condition(s) exist which result in the problem. It may result from extreme climatic conditions such as frequent heavy storms during a period when the soil is bare and chemicals are normally used. The soil may be extremely shallow, tend to crust and seal, thus having low water retention and transmission characteristics. A combination of climate and soil may cause a problem in that the soil surface layer, thawing with warm rain on a frozen profile, results in quick saturation of the thawed layer, and if the slope is steep with little cover, extreme erosion could occur. This condition occurs in many parts of the world. Another problem may result from extreme applications of chemicals; application of animal waste at high rates, and a wide spectrum of pesticide application such as in warm climates with high insect and weed control problems.

Regardless of the extreme problem, careful professional judgement must be exercised when making model application and interpreting the results. For example, a physical chemist without experience and knowledge in agricultural production methods and the associated effects could not be expected to apply and interpret results from the hydrology or erosion components. This is not restricted to CREAMS, but applies to all models. The system being modeled is very complex, and the associated interactions are difficult to represent and assess.

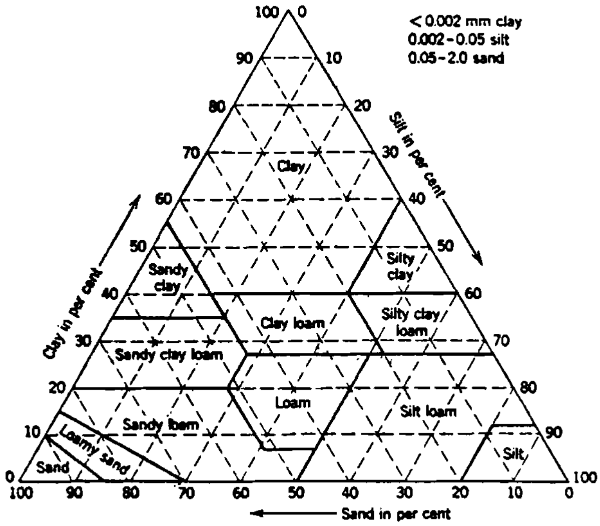

Figure 1. U.S. Department of Agriculture textural classification chart

Table 1. Mean physical properties of soils

Texture	Volume (in/in)						
	Bulk Density gm/cm	Total Porosity	Field Capacity 1/3 bar	Wilting Point 15 bar	AWC	FUL	CONA
Coarse sand	1.6	0.40	0.11	0.03	0.08	0.28	3.3
Sand	1.6	0.40	0.16	0.03	0.13	0.40	3.3
Fine sand	1.5	0.43	0.18	0.03	0.15	0.42	3.3
V. fine sand	1.5	0.43	0.27	0.03	0.25	0.63	3.3
L. coarse sand	1.6	0.40	0.16	0.05	0.11	0.40	3.3
Loamy sand	1.6	0.40	0.19	0.05	0.14	0.48	3.3
Loamy f. sand	1.6	0.40	0.22	0.05	0.18	0.55	3.3
L.v.f. sand	1.6	0.40	0.37	0.05	0.32	0.92	3.3
Coarse s. loam	1.6	0.40	0.19	0.08	0.11	0.48	3.3
Sandy loam	1.6	0.40	0.22	0.08	0.14	0.55	3.5
F. sandy loam	1.7	0.36	0.27	0.08	0.19	0.75	3.5
V.f. sandy loam	1.6	0.40	0.37	0.08	0.29	0.92	3.5
Loam	1.6	0.40	0.26	0.11	0.15	0.65	4.5
Silt loam	1.5	0.43	0.32	0.12	0.20	0.74	4.5
Silt	1.4	0.47	0.27	0.03	0.24	0.57	4.0
Sandy clay loam	1.6	0.40	0.30	0.18	0.12	0.75	4.0
Clay loam	1.6	0.40	0.35	0.22	0.13	0.88	4.0
Silty clay loam	1.4	0.47	0.36	0.20	0.16	0.77	4.0
Sandy clay	1.6	0.40	0.28	0.20	0.13	0.70	3.5
Silty clay	1.5	0.48	0.40	0.30	0.14	0.92	3.5
Clay	1.4	0.47	0.39	0.28	0.11	0.83	3.5

Table 2. Ranges of effective saturated conductivity of soils by hydrologic group

Hydrologic Group	RC (in/hr)
A	0.30 - 0.45
B	0.15 - 0.30
C	0.05 - 0.15
D	0.0 - 0.05

An example of application for extreme conditions is represented by one in the United States where the Soil Conservation Service used CREAMS to consider a wide range of management practices (USDA, 1981). The water quality problem was related to adsorbed pesticide transport into a lake. The soil was a deep, structureless loess with little organic matter and high erosion potential. Soil conditions were such that, even though the soil profile was deep, management practices over many years resulted in compaction and an effective root depth of 8 inches (20 cm). The watershed drainage area was 430 km^2 with approximately 63 percent cropland. Soils and topographic maps showed there was a single dominant soil type. After minimum reconnaisance of the area, Soil Conservation Service technical specialists decided that three field topographic conditions were reasonably representative of the watershed. Three representative fields, ranging from approximately 2 to 9 ha. in size were selected for application of CREAMS. A local 20-year daily climatic record was obtained. Average annual precipitation is approximately 1400 mm. Information on existing management practices was obtained for a comparison, and alternative management practices, both mechanical and agronomic, were developed for simulation. The selections resulted in more than 90 individual simulation runs to evaluate the respective hydrology, erosion, and chemistry response. Management practices were ranked by sediment yield and adsorbed chemical yield to select options for nonpoint source pollution reduction to some acceptable level. Alternative management options were presented to farmers of the watershed for their consideration relative to their personal economic constraints. Cost-sharing practices have been planned and the project will be implemented in 1983 based upon CREAMS application and professional interpretation of results.

This represents a recommended application of an extreme problem. Simulations were made for representative fields to develop alternate management strategies for a large watershed.

CASE STUDY APPLICATIONS OF CREAMS

The foregoing discussion and comments are general in nature, and do not apply to any specific case study. The remainder of this paper will be discussions of each specific study.

CZECHOSLOVAKIA

Two case studies were made in Czechoslovakia using the CREAMS model. The first study (but published later) was on the Samsin research area (Holy et al., 1982), and the second was on the Sedlicky Brook small watershed (Holy et al., 1981). Some parameters calibrated for the Samsin field were used in the application for the mixed land use Sedlicky watershed. In the CSSR case study (Holy et al., 1982), the authors cite several examples where the computer program input/output differs from the description given in the user manual (Knisel, 1980). This discrepancy results from the timing of the study and the time of the model publication. In 1979, the CREAMS model was well into the development and a draft of the publication was available for use. In June of that year, the computer program was stored on the IIASA computer for scientists' use. During the next 9 months before final publication, the model developers found it necessary to make some changes in the program computational procedures, and as a result, some revision of input and output was needed. These revisions were made prior to publication in 1980. At that time, copies of the publication and a new program were brought to IIASA. The CSSR case study used the first model version on the computer. Many of the computer runs had been made by the latter date, and they were not rerun with the latest version, Holy et al. (1982) discussions of the model relate to the advanced program and the final publication. Results of simulation using the two computer programs would not be significantly different.

Estimation of the parameter FUL requires some clarification. The case study (MS. p. 53) gave

$$\text{FUL} = \frac{\text{Field capacity}}{\text{Upper limit of storage}}$$

and field capacity is defined as the soil water content after gravitational water has drained. This definition is slightly incorrect for FUL since the field capacity includes hydroscopic water that is not available to plants, e.g., BR15. FUL should be defined (computationally) as:

$$\text{FUL} = \frac{\text{Field capacity - BR15}}{\text{Upper limit of storage}} = \frac{\text{Field capacity - BR15}}{\text{Porosity - BR15}}$$

where field capacity minus BR15 is the plant-available water. FUL by this calculation will be slightly less than that estimated by Holy et al. (1982). This difference affects percolation, since volumetric percolation basically is (1 - FUL).

The first application of the CREAMS model (Holy et al., 1982) in the CSSR was on the 6 ha. Samsin catchment where observed data were available for hydrology and erosion. Observed data from the 152.7 km^2 Trnaka watershed were used to evaluate the plant nutrient component. Results of the case study showed that average annual runoff simulated was 15% less than observed, whereas average annual erosion simulated was 29% less than observed. There was very low erosion for the period of simulation. Runoff and leached nitrogen simulated for the Samsin catchment was 7% greater than that observed in the Trnaka watershed. It was concluded that the model can be an effective tool for the description of the hydrology, erosion, and chemistry components, but calibration is needed where data are available.

The second application of CREAMS, on the Sedlicky Brook watershed (Holy et al., 1981), was made to evaluate the erosion and plant nutrient processes. Observation data were available for several sites in the watershed. Comparison of observed and simulated data showed good agreement, and it was concluded that CREAMS can be used effectively for erosion and plant nutrient processes on small watersheds as well as for fields.

FEDERAL REPUBLIC OF GERMANY

Application of the CREAMS model in the FRG case study identified a problem similarly detected during an application on forested areas of the USA. The hydrologic and plant nutrient components were used in the FRG study. In the hydrology component, the empirical relationship for potential evaporation was modified to give a 25% reduction in potential. The modification resulted in more favorable comparisons with observed data. Further, percolation was underestimated by CREAMS. Since potential evaporation is overestimated, and this is a part of the water balance, an under-prediction of percolation would be expected.

In the USA, CREAMS model tests on forested watersheds showed similar results: with a measured LAI of 5.5, transpiration in the model occurs at the potential rate*. Field observations showed less transpiration than the model simulated. The explanation is that high-level forest canopy and dense undergrowth reduced the evaporative flux. Caution, or modifications, should be exercised in future applications.

Results of the plant nutrient component in the FRG case study are both gratifying and revealing. CREAMS had not been tested where such high concentrations of nitrate leached. The study results certainly indicate the right order of magnitude. Actually, these results are somewhat misleading. The average annual volume of percolation and reported mean annual nitrate concentration indicates a high nitrate load in groundwater (both observed and simulated). For example, converting these data to load of nitrate results in an observed average annual value of 884 kg NO_3/ha. The total fertilizer N applied over a 4-year period was 377 kg N/ha per year. Conversion of NO_3 to NO_3-N gives 200 kg NO_3-N/ha per year leached. This leaves an average of 177 kg N/ha for plant uptake and denitrification as the principal components in the nitrogen balance. With the high percolation rates, soil water content remains high enough during the year to account for considerable denitrification. The point of this discussion is that the groundwater from outside the surface drainage area may have a sufficient interaction to influence the water quality of the total system, and care must be taken to interpret the model results with the real system represented.

Following the desired model validation for the FRG conditions, the case study made excellent use of CREAMS, as envisioned by the model developers, to consider alternate fertilizer management strategies. A 20-year climatic record was used to simulate nitrate leaching from the agricultural field. The reported results for corn shows significant reduction of NO_3 concentrations when three fertilizer applications per year were made. The difference between the average leached nitrate concentration (110 kg/ha versus 130 kg/ha) may not be statistically or technically significant, but differences in monthly average concentrations certainly are significant. Similar comparisons for winter barley do not reveal such significance. The reporting of results, in this case study, average annual or average monthly values, must be carefully examined in order not to disguise significant features. The estimated leaching functions are quite useful to planners for improving water quality. The general conclusion was that after modifying the potential evaporation coefficient, CREAMS could be used effectively to consider management practices related to nitrate leaching problems.

FINLAND

Application of CREAMS on the Hovi basin in Finland is difficult in that more than one crop is grown each year. The respective areas of wheat, barley, and oats do not sum up to the number of hectares in the basin, and the

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*Nutter, W.L. (1982). Personal communication, University of Georgia, Athens, Georgia.

remaining land use is not known. Leaf area index (LAI) differs for the three crops and it was not stated how the LAI was used, that is, weighted by crop area, for one crop only, or what was used. Since the three crops are closely related cereals, the results of hydrology application may not be seriously in error. If fertilizer was applied at different rates, there may be a larger discrepancy in nitrogen losses. Comparative results between observed basin discharge and simulated runoff plus percolation were relatively good.

The simplified modification of precipitation for snow is rather unique. Use of the latest model version should not require this data modification. The relative time between observed discharge and simulated runoff plus percolation is to be expected as CREAMS does not route the components. Model simulation considers only movement of water through the root zone. Some time element is necessary for percolate to flow laterally to the drainage ditch.

The nutrient loss simulated values do not agree well with observed losses and interpretations are difficult. It was pointed out that sample collection may not have been adequate. This is true, but other factors may be involved. For instance, the basin drainage system and organic carbon content may result in further denitrification losses and causes erroneous calculation of loads.

Another difficulty that occurs in interpreting results is extrapolation on a unit basis. For example, the Hovi basin is 12 ha in size which is 0.12 km^2. CREAMS chemical calculations are in kg/ha such that multiplication by 100 is necessary to determine kg/km^2. The orders of magnitude differences are not merely units of measure, but represent a scale on which the units are measured. Nitrogen fertilizer application rates of 26 and 32 kg/ha were reported in 1968 and 1969, respectively. These are 2600 and 3200 kg/km^2: numerical orders of magnitude and scale. Comparative results for erosion and plant nutrients between observation and simulation are not as overwhelming when scale is removed.

Lithuania, USSR

The case study in Lithuania, represents a regional application of the CREAMS model with weighting of model output by respective area of land use to estimate aggregate basin response. Also, the application recognizes CREAMS as a tool in a larger hierarchy of models to aid in decision-making processes. The selection of a representative basin profile to obtain field-size areas by slope segment is an excellent sampling method. The only problem, in isolating each slope segment to represent a field, might be that runoff from one segment actually cascades onto the next topographically lower segment. If this is the case, CREAMS would not be capable of providing the correct response. If flow from one segment does not cascade onto the next, then there is no problem.

Results reported in the study appear reasonable from the view of technical logic. The only uncertainty about the application relates to the peat soil. CREAMS has not been tested with data from organic-soil watersheds. The only results for peat soils shown for the case study is for hydrology, and intuitively the values appear to be in the right order of magnitude relative to other soils. If the model parameters for peat soil can be obtained, then hydrology results should be relatively good. The uncertainty of model applicability relates to erosion and chemistry. CREAMS was developed for application on mineral soils. The high organic matter content may cause distortion of the erosion relationships. Also, such a high organic carbon content certainly would affect the nitrogen cycle, and results from these processes would be doubtful, that is, mineralization and denitification. Since CREAMS does not include the process of nitrate immobilization, the other processes may tend to get out of balance.

A problem that must be kept in mind when combining results from CREAMS elements to represent a basin is that of routing. Since the model operates with rainfall, runoff, and percolation volumes rather than rates, combining volumes for the basin is all right. The problem is related to routing of sediment and non-conservative chemicals, that is, deposition or further erosion of sediment or movement of chemicals that decay or that may be transformed en route to the basin outlet. Comparison of aggregated results with observed data may not be good in that situation.

The CREAMS model was applied for the small Davila watershed in the Utena region of Lithuania, USSR. Although comparative results were not given in the case study, it was concluded that the model gives comprehensive descriptions of the hydrologic, erosion, and chemical processes. CREAMS hydrology results, combined by land use for the whole Utena region, compared very well with the water balance components calculated, using observed precipitation and runoff in another study. This case study attempted to apply CREAMS to regional problems, but complete methodology of transferring field-level data to regional levels was not solved. Since the climate of Lithuania is similar to that of Finland, similar problems were recognized for snow accumulation, snowmelt, and frozen soil.

POLAND

Some misunderstanding occurred in the application of CREAMS for the Notec River valley*. This should be clarified for possible future model use. The hydrology component of CREAMS gives averages of water balance components for the period of simulation. In the model structure, an arbitrary decision was made to consider a maximum of 20 years for one simulation period. The final soil water content, at the end of a 20-year run can be used to estimate initial conditions (parameter BST) for another 20-year period. Resulting pass files can be linked together for the erosion and chemistry components. These two components do not perform averaging calculations, and output is summed for each process, e.g., erosion, nitrogen uptake, mineralization, etc. If a 50-year precipitation record is available for the application, three separate runs for 20, 20, and 10 years must be made. Average annual and monthly values of runoff, ET, percolation, etc., must be recomputed for the total 50-year period. The three hydrology pass files can be merged to give a single pass file for the 50-year period and run for erosion. An alternative is to make three separate runs for erosion and sum the results. The fact is: 20 years is the maximum record period for a single hydrology simulation, but combined simulation runs can be made to utilize any record period desired.

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*Personal communication between W.G. Knisel and A. Sapek, and also between W.G. Knisel and V. Svetlosanov.

Application of the CREAMS hydrology Option 1 for a crop rotation does not present a problem for changing the SCS curve number. As indicated in the table of parameter values for light-textured soils of the Notec River valley, curve numbers range from 67 to 78. It is not necessary to make four separate 1-year simulations to change curve number. The curve number parameter merely places a lower limit for estimating the actual curve number for individual storms. The curve number, and extended calculations to estimate runoff, is a function of available water storage in the soil profile on a day when rainfall occurs. Therefore, this application would use a value of 67 for the parameter CN2. No further adjustments are necessary. During each year of simulation, there is some time period in which the soil is bare, that is, fallow. For bare, fallow conditions, the curve number would be approximately 80, but it is not necessary to run fallow and growing crop periods separately.

Discussion of the case study results noted possible differences in crop yields and nitrogen uptake between USA and European conditions. CREAMS uses potential yield and plant water use to estimate nitrogen uptake, and potential yield is an index as opposed to an absolute crop yield. Management practices have a carry-over effect on crop production. That is, if fertility is maintained at a high level on a field for a period of years, higher than "normal" crop yields would be expected. The reverse is also true; low fertility results in less than "normal" yields. Of course, this is a function of climate as well. Professional judgement must be used in estimating parameter values that reflect previous management practices.

CREAMS was applied to evaluate nitrogen losses from a field in the Notec River valley, Poland, with a 20-year simulation. The results showed high leaching of nitrate, and the present management practices may not be the most economical fertilizer practices and they may cause a threat to water quality.

SWEDEN

The Swedish case study illustrates a situation where a definite water quality problem has been identified, and there is sufficient national concern to implement research and model application to develop management practices for problem solution. CREAMS was effectively used in the study to provide insight into the problem. Application for the Kävlinge River basin requires two points of discussion concerning supplemental irrigation for light- and heavy-textured soils.

Sprinkler irrigation is necessary for sandy soils to provide uniform water application over a field. The normally high infiltration characteristics generally do not result in over irrigation, that is, causing runoff. Irrigation amounts can be input on specific days in the precipitation data files as was done in this study. This application is good. In the USA, the CREAMS model was modified to internally determine the date to irrigate and amount of irrigation water required to satisfy the soil water deficit (DelVecchio and Knisel, forthcoming). Simulation for different management practices, with and without irrigation, provide estimates of the effects of irrigation.

The Swedish case study for irrigation of wheat on clay soil may pose some problems. If sprinkler irrigation is used, there is no problem because sprinkler-applied water generates water drop energy for soil detachment.

However, if irrigation of clay soils is by flooding where water is applied from a ditch or canal, and if over-irrigation results in runoff, the erosion component of CREAMS would not give good results. First, there are no simulated raindrops and rainfall energy for soil deatchment is zero. Erosion occurs as detachment of soil particles by shear stress of the advancing flow. Next, the hydraulics of the CREAMS erosion component does not match the real condition. CREAMS assumes a runoff generation process that results in spatially varied uniformly increasing discharge. In actuality, the reverse is true. That is, with flood-type irrigation, the process is such that flow is spatially varied uniformly decreasing. The resulting energy gradelines are completely different for the two hydraulic conditions and calculated shear stress would be over-estimated. Also, the peak rate of discharge as used in CREAMS is that for the outlet of the field which potentially has the greatest transport capacity depending upon slope. The peak flow for flood-type irrigation is a constant rate, but more important, it occurs at the ditch or canal, which is at the beginning of the slope and not at the end.

The case study involved application of the CREAMS model to evaluate nitrate leaching for soils and management representative of the Skåne region of Sweden. Although specific field data were not available for model verification, it was concluded that annual nitrate leaching from simulation agreed relatively well with observed values. Results of simulation with daily rainfall and with daily rainfall plus irrigation showed that supplemental irrigation may not be as serious for nitrate leaching as was thought. It was concluded that, although CREAMS is not a prediction model in absolute quantities, it is a model that can be used to evaluate different management practices. The model should be evaluated with research data.

UNITED KINGDOM

In addition to the UK case study included in this publication, an earlier study (Morgan, 1980) is also discussed. The earlier paper was confined to erosion and the present paper considers hydrology as well.

Application of the CREAMS model on the erosion plots at Silsoe is a rather unique modification. First, CREAMS was not developed for application on such a small area as 10 m^2 or 1 m^2. A 1 m^2 area is analogous to a rainfall simulator plot, and response is practically instantaneous. The scientists recognized that peak runoff rates estimated in the CREAMS model would not be valid. Consideration of the rills on the experimental plots as being equivalent to concentrated flow in the model probably is a valid assumption. A more serious question relates to the defined overland flow profile and length of "channel" (rill) for an assumed contributing area of 1 m^2 with a slope length of 1 m. The channel length was not given. It appears that parameter distortion may be significant and the results of simulation may reflect this to some extent.

Comments on some of the statements made in the paper and some parameter values may be helpful to the scientists in future applications. These relate to the hydrology component.

It was indicated that the CREAMS hydrology component would not run with year-long values of LAI = 0. This is a computer-dependent problem that results in a program ABEND--abnormal end of program execution. Within the model, the LAI is divided by the maximum LAI during the year merely to determine the decimal fraction of each day's LAI to the maximum value. Some computer systems stop execution because of the error severity, while other operating systems apply a "Standard Fixup". Simulation results, that is, soil water evaporation, runoff, percolation, etc., are not affected by the standard fix. The computer job runs and the results are correct. This was tested on IBM and CYBER computers. A very small value of LAI for 1 day will prevent the fatal error from occurring. For example, LAI = 0 on day 364, LAI = 0.01 on day 365, and LAI = 0 on day 366 will prevent execution termination, and the results will be practically identical with those from standard fixes. The method used by the authors is satisfactory and it did not adversely affect the results.

Caution must be exercised when simulating a shallow soil profile and low effective root depth (RD). Tests have been made in the USA for RD = 6 inches and execution failed. This is soil dependent, but irrespective of soil, a 6-inch root zone results in a top layer thickness of 1/6 inch which has infinitesimally small water storage characteristics. Overall model interactions affect the lower limit.

It was stated that runoff is independent of drainage area size. Runoff volume estimated in the model is expressed as an equivalent depth of runoff over the field, and as such, it is independent of area. Peak rates of runoff are directly related to drainage area raised to a power.

The CREAMS model was applied on the bare, fallow, erosion plot at Silsoe, Bedfordshire, UK. It was concluded, from comparing the hydrology component simulation results with observed runoff, that CREAMS is promising as a tool for simulation, but that it should be calibrated for the condition there. Additional studies are desired for woodlands, grasslands, disturbed lands, and recreational areas, and efforts should be made to define better some model parameters for UK conditions.

The erosion submodel was evaluated with data from 33 storms over an 8-year period. Good correlation was achieved between simulated and observed storm erosion. As in the hydrology component, the erosion submodel showed promise as a tool for UK conditions, and further analysis is desired for all plots with slopes of 3^o to 11^o.

SUMMARY

The applications of the CREAMS model in these case studies have resulted in identification of model limitations and areas which call for improvements. Also, they have shown that CREAMS gives generally good results and the model is a tool that can be used to aid in development of agricultural management practices for nonpoint source pollution control. Validation with observed data has shown that CREAMS is a suitable model for extrapolating research results to other climatic and soil regions. Although the model gives reasonable results in simulation, it is desirable to calibrate it with data where possible.

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P A R T IV

C R E A M S 2

W.G. Knisel

INTRODUCTION

The CREAMS model was developed as a state-of-the-art model to evaluate nonpoint source pollution from field-size areas (Knisel, 1980). It represented an assembly of readily available components, or modification and adaptation of elements within a short time frame, so as to be available to users. Although CREAMS has proven to be a good tool for users to evaluate effects of agricultural management practices on nonpoint source pollution, it was recognized as having many limitations. At the time of publication in 1980, plans were made to improve the model and make it more comprehensive. Feedback from users, such as the U.S. Soil Conservation Service, Environmental Protection Agency, and IIASA, was expected to aid in identifying elements that needed replacement or improvement, and also to identify new elements that should be incorporated. As a result of discussion with these and other users, many items were brought to the attention of the scientists who developed CREAMS, and a significant effort is in progress to make the necessary and desired improvements, but details of actual process formulations will not be given.

OVERVIEW

The CREAMS model was developed with the idea that a user: (1) has some observed data and wants to simulate other components, i.e., he has observed runoff data and desires to simulate erosion, (2) only wants to simulate runoff and erosion but is not interested in chemistry, or (3) desires to make simulations for all components. Also, it was desirable to be able to run the model on relatively small computers. In order to meet these requirements, it was considered expedient to separate the components and run them individually by generating and using passfiles, that is, generating a file of output such as from hydrology and later using that file as input to erosion. This was effective but it resulted in some limitations such as incomplete or averaged information without proper feedback from one component to another. For example, crop growth is simulated in the hydrology component and is adjusted for soil water stress. However, by applying the plant nutrient component with a passfile, crop growth cannot be adjusted for nitrogen stress. Likewise, some parameters were required for more than one component, such as temperature, soil porosity, organic matter content, etc. Input of parameters was not as streamlined in one component as they were for others. Many cards (lines) of input parameters were required for erosion and chemistry compared with that for hydrology.

To overcome these limitations, CREAMS 2 will operate as a single package with appropriate interaction of components. This will eliminate the problems of file manipulation and cataloging but will require more computer storage. Since output is simultaneous with computations to overcome storage, a large total output file will be generated with general summary data printed. The total data file can be used with subsequent programs to generate reports of intermediate data. This will enable the user to get all available information in a single run and be able to retrieve intermediate data as desired at a later time.

A management component will be included in CREAMS 2 that will relieve the user from specifying depth of tillage, resultant surface roughness, etc. These elements will be a part of the computer program with selection of tillage type by appropriate codes and dates. The dates will be used to denote updates of those parameters that are affected such as porosity of the tilled layer, Manning's n-value for flow retardance, and possible change in soil loss ratio.

The period of simulation for CREAMS 2 will not be limited. A single storm, such as a design storm, can be simulated with the model, or 1 month, 1 year, 2 years, 10 years, 50 years, or whatever period is desired. The only limit will be the amount of input data that a user has available or that he wants to provide.

Although a climate generator is not included in the model, the program is structured so that a climate generation model can be used to generate precipitation, radiation, and maximum and minimum temperature.

Such a generator model is being used in the United States for limited application. The model requires regional parameters for daily rainfall, radiation, and temperature. Although the model has been tested, parameters have not been developed for many different climatic regions.

An hourly rainfall model is being developed in the U.S. Department of Agriculture, Agricultural Research Service. Although the model structure is available, regional parameters and regional testing have not been completed.

Use of climate generators will relieve the user of the burden of locating long-term records and entering them into the computer. Also, long-term data (50 or 100 years) is much more appropriate for risk analysis associated with nonpoint source pollution.

HYDROLOGY

Some of the items that are discussed under this heading are not strictly hy rologic processes. However, they impact on the hydrologic response of a management unit either directly or indirectly. Further, they may be instrumental in or impact on processes of other components. For example, air and soil temperature affect the hydrologic response by directly affecting snowmelt and infiltration, but also affect crop growth which further affects soil evaporation and plant transpiration. These, in turn, affect and are affected by soil water content of the soil which affects the division of precipitation into runoff, infiltration, and percolation. Therefore, CREAMS model improvements related to these and possibly other factors will be discussed under the hydrologic component. Reference will be made in other components where their effects impact on the overall response.

The hydrologic component of CREAMS 2 is being made more consistent among the various methods of computing runoff, percolation, and water balance. A major improvement is the layering of the root zone soil profile with the layers corresponding with the soil horizons. Properties, or characteristics (texture, porosity, water retention, conductivity, etc.) are defined for each horizon, and the model further divides the horizons into computational layers to improve percolation routing through the root zone. Such layering will permit consideration of claypans, plowpans, or other restrictive conditions that affect the root development and water movement. Soil layering will further improve the model representation for nitrogen transformations and plant uptake, and the vertical flux of pesticides which were not included in the first model.

A soil temperature model has been developed to permit estimation of frozen layers with associated changes in water conductivity, infiltration, and percolation. In many regions of the world, snowmelt occurs in the spring when air temperature exceeds 0°C, but the soil is frozen to some depth and runoff occurs. Also, some regions oftentimes have a warm rain falling on a snowpack. The warm rain may thaw the surface 1-2 cm of soil, quickly saturate the surface which overlies a frozen layer, and large volumes of runoff and erosion result. The combination of soil layering and soil temperature will enable the model to better approximate these conditions.

The snowmelt component of CREAMS will not be modified significantly in CREAMS 2. Improvements mainly will be that for frozen soil and the use of daily maximum and minimum temperatures rather than the mean daily temperature. Maximum daily temperature, frozen soil layers, and zero conductivity will permit the model to generate large volumes of snowmelt runoff when snowpack accumulations are significant.

The percolation component will be improved by routing pulses of drainable water through the soil layers having variable conductivity. In CREAMS, the concept of field capacity was used, and field capacity is defined as the water retained in the soil after 24-hour drainage. This resulted in all the percolation volume occurring in one day. Boundary conditions imposed by restricting layers does not permit this in many soils in the real world situation, thus the estimated soil water state, at some later time, was in error. This improved percolation process should improve the overall model response.

In CREAMS, there were two options in the hydrology component for estimating surface (direct) runoff: (1) the daily rainfall option, and (2) the Green and Ampt infiltration option. CREAMS 2 will contain a third option which is a fully dynamic infiltration approach using the Green and Ampt parameters, but will generate the storm hydrograph using the kinematic routing. The generated hydrograph will not be coupled with erosion and chemistry to produce a sedigraph and a chemigraph, but it will interact with erosion and chemistry to better define conditions and states between the points at beginning of rainfall and the end of runoff.

The hydrologic component of CREAMS considered plant stress due to soil water, but by the 3-component structure of the model, interactive stress for nitrogen deficiency was not possible. The interacting structure of CREAMS 2 and inclusion of a soil temperature component along with maximum and minimum air temperature will allow the model to constrain plant growth for water, temperature, and nitrogen stress. This is not to imply that CREAMS 2 will have an accurate plant growth model, but the overall processes will be more adequately defined.

EROSION

The erosion component of CREAMS, with some slight modifications, will be the principal component in CREAMS 2. The major difference will be the simplification of input parameters. Input will be reduced drastically for those parameters that change as a function of crop growth and tillage. For example, if a single crop rotation is repeated during the simulation, and generalized application is made, that is, the planting-tilling-harvesting dates are assumed to be the same each year that crop appears in the rotation, the updateable parameters will not have to be repeated each year the crop occurs in the simulation. The updateable dates and narameters merelv will be read and stored initially, and recalled for use in each applicable year of the simulation. This reduction may be from as much as 800 cards (lines) to 50 cards for a 3-year crop rotation and a 15-year simulation period. The change in output results will be negligible, that is, streamlining input will not affect the relative accuracy of the erosion model.

A dynamic erosion option will be available to the user of CREAMS 2 for application with the dynamic hydrology option. Empirical relationships have been developed to relate some of the updateable parameters, such as the Manning's n-value and soil loss ratio that change most frequently, to tillage surface condition, crop growth, and crop residue. Base values of these parameters will be input and they will be adjusted internally in the model. In CREAMS and in the "streamlined" erosion component of CREAMS 2, changes in these parameters were abrupt, stair-step type changes made externally. In the dynamic version of CREAMS 2, there will be both abrupt and smooth transitional changes which are more representative of the system being modeled. For example, n-values change abruptly when the soil surface roughness changes due to tillage, but n-values change graduallv with time and rainfall following a tillage operation and with crop growth. Likewise, the soil loss ratio changes gradually with crop growth; it changes abruptly at crop harvest, and it changes gradually with crop residue decomposition.

PLANT NUTRIENTS

The plant nutrient component of CREAMS was rather restrictive in application because all necessary input and formulation of cycle processes were not available at the time of development. The major components of the nitrogen cycle were included to give adequate respresentation of response to inorganic fertilizer application, that is, nitrogen in runoff, nitrogen with sediment, and nitrate-nitrogen leached, which are the parts of concern in nonpoint source pollution. It was recognized, however, that some important components were omitted. They are being incorporated into CREAMS 2.

Mineralization of organic matter and denitrification processes are affected by soil water content and temperature. The soil temperature model, and soil water content by layer will improve the model representation of the modeled system. In CREAMS, average soil water content in the root zone and mean daily air temperature were averaged between rainfall events, and these average values were used to adjust the process rate constants for the period between events. The time step between events in CREAMS 2 will be one day, and the processes will be calculated for each soil layer using the respective soil water content and soil temperature for the layer. This will provide better representation of field conditions, and will permit possible mineralization in the upper layers and denitrification in the lower layers simultaneously.

Nitrogen fixation by legumes was not included in CREAMS because legumes do not assimilate (fix) nitrogen in excess of their needs and release it to the soil during the growing season. However, nitrogen assimilation is important in the overall nitrogen balance, especially when a perennial such as alfalfa is grown in a rotation. Fixation will be included in CREAMS 2 to be able to represent such important crops as soybeans, peanuts, alfalfa, and several vegetable crops.

Land application of animal waste and sewage treatment effluent is an important management practice in many countries. Organic nitrogen application and transformation are included in the improved model. Water quality problems in many lakes have been linked to nitrogen and phosphorus runoff from animal waste disposal. Alternate management systems are needed to reduce or minimize the problem. Both liquid and solid waste is considered with application on the soil surface, incorporation by tillage, or injection of a slurry. Multiple applications of waste can be considered, such as daily application by sprinkler irrigation of dairy barn wash water.

The phosphorus component of CREAMS 2 will include vertical movement of soluble P, and will include phosphorus uptake by plants. The phosphorus in runoff and sediment will remain relatively unchanged.

PESTICIDES

The CREAMS pesticide component was found to be sufficient for highly adsorbed insecticides and herbicides, with foliar, soil surface, and incorporated application. The main difficulty was for highly mobile pesticides and injected fungicides and nematicides. The model did not consider any pesticide further than infiltration from the top 1 cm of soil into the root zone. There are nonpoint source pollution problems associated with the highly soluble and highly mobile pesticides that percolate through the root zone and they may appear in groundwater or subsurface return flow downstream. Therefore, the CREAMS 2 pesticide component will include vertical movement to estimate the load percolating through the root zone, analogous to nitrate leaching.

MANAGEMENT

The management component of CREAMS 2 will provide considerable user flexibility. For example, if a user has observed records for a field, and wants to compare model simulation with observed records, it will be possible to specify dates of tillage, planting, harvesting, irrigation, fertilization, etc. If, however, a user wants to make long-term simulations and knows approximate dates of these operations, the model will determine the dates of tillage internally. It will compare soil water content in the tillage layers with a threshold value (possibly 75% plant-available water), and tillage operations will not be applied until the simulated soil water content is reduced below the threshold value. Also, by coding the type of tillage operation, such as for moldboard plow, disk harrow, cultivator, etc., the depth of tillage and amount of crop residue remaining on the surface will be determined in the model. Mixing efficiency, such as with fertilizer application, will be included in the management component.

Irrigation scheduling can be provided by the management component. Supplemental irrigation, in the actual field situation, is often based on some minimum soil water content, and application amounts are just sufficient to raise the water content of the profile back up to that of field capacity. The threshold level of soil water content in the upper soil layers when the model user wants irrigation applied can be specified, and the model will determine the date and amount of irrigation water to be applied. An alternative option to the user is to modify, before the simulation, the precipitation file for the specific day and amount of application.

Another feature of the management component relates to the tillage practice of subsoiling (Untergrund) to break a plowpan or compaction layer. Subsoiling is practiced at intervals of a few years to permit water and plant root penetration, and the effectiveness decreases with time and machinery operations as a function of soil water content. The model will reset saturated conductivity of the layer subsoiled, and adjust the new value with time until effectiveness ends.

Other features will be included in the management component to make the overall model more adaptable to real field operations. Also, the model structure will be simplified for user application and convenience.

SMALL WATERSHED MODEL (SWAM)

There is a project in the U.S. Department of Agriculture, Agricultural Research Service, to develop a mathematical model for evaluating nonpoint source pollution from small watersheds. Although the SWAM (acronym for Small WAtershed Model) project* is separate from the CREAMS project, SWAM will use the CREAMS 2 model to generate source response from unit-management size areas. SWAM will consider watersheds up to about 15 km^2 in size.

Response from the CREAMS elements will be routed into and through the channel system to the watershed outlet. The purpose of SWAM is to evaluate the downstream effects of agricultural management systems on nonpoint source pollution.

Output from the CREAMS elements, that is, surface runoff, percolation, sediment, and soluble and adsorbed plant nutrients and pesticides from field size areas, will be routed by SWAM to the watershed outlet. Although the model has not been completely formulated, the basic structure has been conceptualized by the developers. It will be a physically-based model that will not require calibration for the simulation mode. As is the case with CREAMS, SWAM will not be a predictive model in absolute quantities. However, it will be a valuable tool to estimate the aggregate effects of alternate agricultural management practices on nonpoint source pollution from small watersheds.

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*The project for development of the SWAM model is coordinated by Dr. D.G. DeCoursey, U.S. Department of Agriculture, Agricultural Research Service, Fort Collins, Colorado, USA.

P A R T V

CONCLUSIONS

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GENERAL CONCLUSIONS

The case studies indicate some very important facts that point to the need for physically-based models. Through the case studies some important conclusions developed, especially about the CREAMS model applications.

First of all, the problem of the environmental consequences of agricultural management exists in many countries of Europe and in the USA. Therefore, a mathematical tool is needed for proper investigation of these problems. The size of the problem and the nature of the environmental consequences are not the same in all locations. For example, sediment may be the primary pollutant in one location, but in another area which has sandy soils with a flat topography, erosion and sediment is not a concern but nitrate leaching to groundwater may be important. Another location which has little groundwater and much direct runoff, nitrogen and phosphorus losses from fields may cause a eutrophication problem in lakes. Since field observations and laboratory analytical procedures are time-consuming and expensive, only the most important components of the situation are measured. Very seldom do we find observed data for the complete system--runoff, percolation, erosion/sediment yield, nitrogen in runoff and sediment, nitrate leached, and pesticides in runoff and sediment. Even in the USA where there is extensive agricultural research in diverse soil and climatic regions, it is extremely difficult to find complete data at one location. There was only one such location where data were available at the time CREAMS was developed, Watkinsville, Georgia. Even at Watkinsville there were no data for percolation and leaching because this component was not significant there.

Water quality planners cannot be expected to have or learn to use a different model for every problem or location. This is the very reason that the physically-based CREAMS model was developed. Model testing in the United States had to be made with a partial data set from one location to test a particular model component, and another data set from a different location to test another component. This was a common observation among the case studies in Europe.

Although application of a model, either in validation or simulation, requires considerable scientific effort, sound interpretations of the results may be more difficult. Since the model and situation being studied are complex interactions of climate, soil processes, and management, it is necessary to have a good understanding of both the model and the forces to make good interpretations. It requires application of sound professional judgement. Many conclusions are presented in the case studies, and the most important ones are summarized here. One very significant conclusion can be made. The training and experience of the individual scientists involved in the case studies are very diverse. The CREAMS model is, admittedly, very complex. Yet, these scientists were able to take the model publication, and with a minimum of training in application, make their respective case studies and interpret the results.

SPECIFIC CONCLUSIONS

Conclusions were made in each case study, depending upon the respective application of CREAMS. Several conclusions were similar for different cases

The following is a summarised list from all the case studies:

- The CREAMS model generally gives good representations of the hydrology, erosion/sediment yield, and chemical processes.
- The model shows promise for future application in European conditions, but revision and addition of some processes are needed, e.g., snowmelt, frozen soil, percolation, leaching, and application of organic fertilizer.
- CREAMS is not a predictive model in absolute quantities, but is a useful tool for evaluating effects of alternate management systems.
- CREAMS should be calibrated when observed data are available for testing. Empirical coefficients in the model should be evaluated for European conditions, e.g., evaporation coefficients, rainfall energy relationships, and runoff rate coefficients.
- CREAMS is a field-scale model, but it may be a foundation for some regional studies, and it may be used effectively as a component of larger watershed models.
- Scientists currently are working to develop an improved and more comprehensive model--CREAMS 2. Improvements will help to overcome some of the problems identified by the case studies and will include: soil temperature component, snowmelt/frozen soil, improved nitrogen cycling components, vertical flux of pesticides, and a totally linked (single) model structure to facilitate complex process interactions and model feedback. Further, input of parameters will be simplified for more efficient user application.